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Hydrologic Engineering Center

Methods Systemization Manual

Reservoir Storage-Yield Procedures

May 1967

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Procedures are presented which can be used to determine the relationship between reservoir storage capacity and reservoir yield for a single reservoir. Non-sequential and sequential methods for reservoir yield analysis were described in detail. Other topics included: guidelines for selection of technical procedures; data requirements; use of generalized and simulated data; establishment of study criteria; and, development and use of rule curves.

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FOREWORD

This manual describes technical procedures currently used for determination of storage-yield relationships for a single reservoir. It also contains information for use in formulating plans of study for storage-yield analyses and background information which should be useful in evaluating alternative technical procedures employed at almost every stage of the study.

Due to the variety of problems encountered in storage-yield analyses for various areas and the necessary differences in technical procedures for solutions of these problems, no real attempt has been made to systemize a single procedure for general use. However, each of the several methods described has been discussed in sufficient detail to permit its use by engineers with a background in hydrologic engineering.

The manual is oriented toward the needs of the engineer engaged in the analysis of storage-yield relationships, and therefore, the emphasis is upon the practical aspects rather than the theoretical. Much of the information is not available in contemporary textbooks and, for this reason, it is believed that the manual will be a useful reference for the experienced engineer as well as a basic guidebook for the beginner.

This manual is issued on a provisional basis because future additions and revisions are contemplated. Users are encouraged to notify the Hydrologic Engineering Center of any desirable additions or revisions.

As a project of the Training and Methods Section of the Hydrologic Engineering Center, the manual was prepared under the supervision of Bill S. Eichert, who also contributed to its content. Much of the research and writing was done by Augustine J. Fredrich on special assignment from the Special Projects Section.

RESERVOIR STORAGE-YIELD PROCEDURES

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PLATES

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INCLOSURES
(Bound Separately)

RESERVOIR STORAGE-YIELD PROCEDURES

1. INTRODUCTION

a. Purpose. The purposes of this manual are: (1) to provide the engineer engaged in planning and design of reservoir projects for conservation purposes with a summary of technical procedures currently in use for analysis of storage-yield relationships; (2) to present systemized procedures and detailed computation examples illustrating these procedures; and (3) to encourage the use of appropriate systemized procedures whenever possible in order to reduce costs of studies, improve quality of results, and facilitate review by higher authority.

b. Scope. This manual presents discussions and methods for analysis of storage-yield relationships in a single-purpose or multipurpose reservoir. Storage requirements for hydroelectric power, water quality, water supply, and other conservation purposes may be determined by methods described herein. Although the discussions and examples are limited to single reservoir analysis, many of the principles are generally applicable to multi-reservoir systems. However, the techniques for analysis of a multi-reservoir system are, as a rule, considerably more complex than those described herein and will be presented in another systemization manual to be issued in draft form in FY 1968.

c. Description of the problem. The determination of storage-yield relationships for a reservoir project is one of the basic technical activities associated with the study of low-flow regulation by reservoirs. Plate 1 illustrates in chart form the realm of activities included in low-flow regulation studies. This manual refers to studies required in Block 3.2b of Plate 1. Briefly, the problem of determining storage-yield relationships might be described as the application of various theoretical and empirical methods to hydrologic data in order to determine the regulating effects of a reservoir project. The step-by-step procedures involved in storage-yield studies are shown in chart form on Plate 2.

2. GENERAL PROCEDURES

a. Detailed Methods. Current methods for determining reservoir storage requirements necessary to produce specified yields are based upon detailed sequential routing studies or upon certain simplified analysis. The most common method consists of performing a sequential reservoir routing (operation) study which simulates the operation of a reservoir project through the period of historical flow record. The results obtained by use of this method may be rigidly controlled by the engineer directing the study. Assuming adequate data available, the studies can be made as detailed as time, manpower, and money will permit.

b. Simplified Methods. If demands for water are relatively simple or if approximate results are sufficient, as in the case of many preliminary studies, a simplified method is often used to save time and money. However, it should be emphasized that the objective of the simplified methods is to obtain a good estimate of the results which could be achieved by detailed sequential analysis. Simplified methods consist generally of mass curve and depth-duration analyses discussed in paragraph 9.

c. Computer Techniques. The advent of the electronic computer has changed the role of the simplified methods because of the relatively low cost of a detailed sequential routing utilizing computer programs such as the Hydrologic Engineering Center's programs 23-J2-L245 and 23-J2-L253. The increasing feasibility of the detailed sequential routing study has not eliminated the need for simplified methods entirely, because these methods now become valuable tools for use in obtaining good estimates of input data for the sequential routings by electronic computer.

d. Potential Future Needs. In the past, detailed sequential routings have been used almost exclusively for development of operating plans for existing reservoirs and reservoir systems. Planning studies, on the other hand, have been based almost entirely on simplified methods. However, the advent of the comprehensive basin planning concept, the growing demand for more efficient utilization of water resources, and the increasing competition for water among various project purposes are indicating a need for detailed sequential routings in planning studies. It is doubtful that simplified methods will be adequate for even preliminary analyses of individual projects in a reservoir system because of the inability of the most sophisticated simplified method to account for hydrologically integrated system operation. In order to provide the optimum benefit from water resources development, the planner and hydrologic engineer must work together in the planning stage to produce a reservoir or reservoir system with a plan of operation which will efficiently and economically utilize and control all available water. The use of detailed sequential routings by electronic computer in hydrologic analyses for planning will be of major significance in achieving these objectives.

3. EXPLANATION OF TERMS

Variations in usage throughout the country prohibit the recommendation of all-inclusive definitions for overall adoption. However, the explanations given in Appendix 1 have been adopted for use in this manual. Additional definitions may be found in ASCE M and R No. 43, "Nomenclature for Hydraulics".

4. OBJECTIVES OF STORAGE-YIELD STUDIES

As a rule, the objective of a storage-yield study is the determination of the storage required to supply a given demand at a specified storage tolerance. However, in some cases it is necessary to determine the yield available from a fixed storage under given hydrologic conditions. In either case, the project purposes under consideration and their inter-relationships will be of importance in selection of the method of analysis. The effects of various project purposes on storage-yield analyses are discussed in Appendix 2.

5. INFLUENCES OF VARIOUS CONSERVATION PURPOSES ON STORAGE-YIELD ANALYSES

The seasonal variation of demand schedules may assume an important role in the determination of required yield. The effect of the seasonal variation is most pronounced when the seasonally varying demand is large with respect to other demands and is often the case when hydroelectric power or irrigation is a large demand item. The quantity of yield from a specified storage may be over-estimated by as much as 30% when a uniform yield rate is used in lieu of a known variable yield rate. Since the detailed sequential routing is particularly adaptable to the use of variable demand schedules, every effort should be made to incorporate all known demand data into the criteria for a sequential routing. It should be emphasized that variable demand schedules often complicate the analysis of reservoir yield to the extent that it is impossible to accurately estimate the maximum yield or the optimum operation by approximate methods. Thus, successive trials using detailed sequential analysis must often be used to determine maximum yield. Computer programs such as those discussed in paragraphs 10b and 10c are most useful for successive sequential routings. The project purposes which often require analysis of seasonal variations in demand are discussed in more detail in Appendix 2.

6. DETERMINATION OF YIELD REQUIREMENTS

Demand data for various water services are ordinarily obtainable from prospective users or other agencies charged with responsibilities for developing such data. The Federal Power Commission, Federal Water

Pollution Control Administration, U.S. Bureau of Reclamation and other federal and state agencies may contribute demand information. In order to coordinate or supplement data obtained in this manner, or in other to make preliminary studies, certain generalized demand data are useful. Therefore, generalized data are presented in Appendix 3 for use in preliminary studies when there is an absence of definitive demand data.

7. DETERMINATION OF PHYSICAL AND HYDROLOGIC CONSTRAINTS

The existence of physical and hydrologic constraints may, in some instances, be of major importance in deciding upon the method of analysis to be utilized. Physical constraints which might be of importance include turbine discharge capacities, outlet capacities, and channel capacities. Other constraints include relative priorities among purposes, storage boundaries, and multiple-use facilities. The effects of various constraints are discussed in more detail in Appendix 4.

8. COMPILATION OF BASIC DATA

Before initiating a storage-yield study, the study objectives and data available for use in the study should be examined in order to ascertain: (1) which computation method is most suitable for the study requirements; (2) the degree of accuracy required to produce results consistent with the study objectives; and (3) the basic data required for the desired accuracy using the selected method. In studies of a preliminary nature, limitations in time and funds might dictate the data and method to be used and the accuracy obtainable. A technical study work plan is very useful in organization of study objectives, inventory of available data, selection of general procedures, etc. The preparation of technical studies work plans is covered in detail in reference 24. A discussion of pertinent considerations regarding compilation of basic data is given in Appendix 5.

9. SIMPLIFIED STORAGE-YIELD PROCEDURES

a. Sequential Mass Curve Procedure. The storage required to produce a given yield can be estimated from the sequential mass curve using the method shown on Plate 3 and often referred to as the Rippl Method. The mass curve in units of volume (cfs-month in this case) is constructed by accumulating the inflows throughout the period of record and plotting the cumulative inflow versus the sequential time on arithmetic paper. The desired yield can be represented by a straight line with a slope equal to the desired yield rate in units corresponding to the flow units. The desired yield must, of course, include the average evaporation during the critical period, and the net yield (yield remaining after evaporation) must represent the average demand for water during the critical period. After the mass curve is drawn, lines are constructed parallel to the desired yield line and tangent to the mass curve at each low point and at the highest preceding tangent point. The vertical difference between these two lines represents the storage required to provide the desired yield during the time period between the two tangent points. The maximum difference in the period of record is often used to determine the required storage. This method is most useful for uniform yield rates since, as shown on Plate 1, Appendix 5, seasonal variations in yield rates may not be accurately represented by an equivalent uniform yield rate.

b. Non-Sequential Mass Curve Analysis

(1) The Sequential Mass Curve method does not directly indicate the relative frequency of a shortage. However, by using non-sequential methods similar to those presented by John B. Stall in reference 12, a curve of storage yield vs. shortage frequency can be determined. The simplified method presented in this manual differs from the method presented by Stall in three ways:

(a) The median plotting positions are used as outlined in reference 3 instead of the so-called "California Method" used by Stall. These correspond to sample size equal to the number of continuous years of record less the duration of drought considered.

(b) Streamflow records are sometimes supplemented by the use of simulated streamflow (as outlined in reference 16), instead of using the "Curve of Relation" proposed by Stall.

(c) The non-sequential mass curves are smoothed graphically to insure mutual consistency. The graphical smoothing is analagous to analytic procedures shown on Exhibit 20 in reference 3 for flood volume frequencies.

(2) The historical flows, supplemented by simulated flows where required, are used to determine frequency tables of independent low-flow events for several durations. The HEC computer program shown as Inclosure 2 is used for this purpose. A series of low-flow events for a particular duration is selected by computing and arranging in order of magnitude the independent minimum-flow rates for that duration for the period of record. The procedure utilized in the program can also be used for manual computation, but the time required for complete analysis is often prohibitive. Plate 4 shows the procedure for manual analysis of a 6-month duration low-flow volume.

(3) After the frequency tables of independent low-flow events are computed for various durations, low-flow frequency curves are obtained by plotting the average flow in cfs on log probability paper. Curves are then carefully drawn for various durations, as shown on Plate 5, making sure that they are mutually consistent.

(4) Minimum runoff-duration curves (Plate 6) for various frequencies are obtained by plotting points from the low-flow frequency curves on logarithmic paper. The flow rates which are in cfs for Plate 5 are converted to a volume for Plate 6 (thousand acre-feet in this example). The logarithmic scales used simply permit more accurate interpolation between durations represented by the frequency curves. A non-sequential mass curve (Plate 7) is simply the selected volume-duration curve plotted on arithmetic grid in order to determine the yield. To determine storage requirement, a straight line with slope equivalent to the required gross yield is plotted tangent to the mass curve. The absolute value of the negative vertical intercept represents the storage requirement. The application of this procedure is severely limited in the case of seasonal variations in runoff and yield requirements, because the non-sequential mass curve does not reflect the seasonal variation in flows, and the tangent line does not reflect yield variations. Hence, storage requirements determined by this method can be erroneous.

(5) By using simulated streamflows, the low-flow frequency curves can be constructed with much less adjustment and with more reliability, as can be seen by comparing Plates 5 and 8. It should be noted that the abscissa of Plates 5 and 8 is "non-exceedance frequency per 100 years"; or in other words, the number of events that can be expected in the 100 years to have that flow or less. It is especially important when considering multi-year flows that the above terminology should not be confused with probability. For instance, the maximum number of independent events of 120 months (10 years) duration in one 100-year period is 10; therefore, the 120-month curve cannot cross 10 on the "non-exceedence frequency per 100-years" scale. If probability is desired, the plotting positions must be computed by using the number of possible events in the sample being analyzed as the "years of record". The abscissa scale would then read either "probability" or "percent chance".

(6) Since computation of the reservoir yield by this simplified method for various reservoir storages and various frequencies may be required, a computer program (Inclosure 3) has been developed for that purpose using a procedure proposed by Robert S. Gooch as shown in reference 9. Plate 9 illustrates the results.

10. STORAGE-YIELD ESTIMATES BY DETAILED SEQUENTIAL ANALYSIS

a. Sequential analysis is the most accepted method of determining reservoir storage requirements in the United States today. For preliminary type analysis, many simplified methods have been proposed and are being used; however, these methods are giving way to the more sophisticated computer approaches. In many fields of science and engineering, the computer provides more accurate answers at a cost equal to or below the cost of preliminary estimates.

b. A reservoir yield computer program developed by the Hydrologic Engineering Center is furnished as Inclosure 1. This program will perform multipurpose reservoir routings for a single reservoir operating for services at the reservoir and at one downstream control point. The releases from the reservoir are determined by the individual requirements for the many purposes. The reservoir releases may be controlled at the damsite by hydroelectric power requirements or by a low-flow requirement or by a downstream control for flow, diversion, water rights or quality. Additional releases may be made to a pipeline directly from the reservoir. The downstream flow requirement determines releases from the reservoir needed to supplement runoff from the intervening area.

c. A computer program for multipurpose multi-reservoir routings is also available in the Center for determining yields where the reservoir projects are not independent. This report was distributed to Corps offices with SPKGH letter of 24 October 1966.

d. The types of form often used for manual sequential routings are shown as Plates 10 and 11. The example routing computations presented on Plate 10 show the general procedures used in the Hydrologic Engineering Center's computer program on Reservoir Yield (23-J2-L245), and generally reflect the detailed step-by-step procedures required by hand methods. The example problem is for a single reservoir which serves several requirements at the dam and at one downstream point. Some of the columns shown would not be used in normal hand computations, but are shown to facilitate a comparison with the computer printout. The speed at which computations are made by electronic computers enables the use of more detailed examinations than would otherwise be practical if done by hand methods.

e. It is desirable to show operations for each period on a single sheet so that each controlling factor may be readily examined. Therefore, a suitable form for the particular operation, such as Sheet 5 of Plate 10, should be developed. Reservoir operation requirements and basic information for the inflow and local flow are tabulated for each period. Unless the controlling factor is obvious, required releases are determined for each operational requirement and the largest required release up to outlet or channel capacities is used. The downstream accomplishments for the selected release for that period are then computed.

f. In most cases, the controlling factor can be located from inspection. During period 10/50 in the example routing, the inflow is sufficiently high to more than satisfy all other requirements, which makes it obvious that evacuation of flood control storage will control. It is then unnecessary to compute releases required for power, quality and downstream flow requirements for that period. However, these were determined in the example problem only to show that the minimum releases required to satisfy each particular requirement were met. The underlined value for each period is the required controlling release for that period.

g. Basic data and reservoir operational requirements are listed in the appropriate columns. Each column is described in detail in Plate 10. Routing computations for each period progress from left to right on the example form. All columns through 17 must be determined for each period. Except for basic data, determination of columns 18 through 31 are optional depending on controlling requirements. Columns 32 through 34 are the accomplishments for which the reservoir was operating.

11. STORAGES REQUIRED FOR SIMULTANEOUS SUPPLIES OF DIFFERENT DEPENDABILITY

a. When storage requirements for two or more project purposes are determined for different probabilities of shortage (such as 2% and 10% probability of shortage), need arises for a method to determine the total storage requirement for two project purposes and the reservoir level below which the lower-priority purposes will not be served. Simplified procedures are illustrated in reference 23 and in the following paragraphs. These procedures should be sufficiently accurate for preliminary studies, but final studies require detailed reservoir routings according to the plan of operation throughout the length of flow record available. Determination of total storage requirement and cut-off storage level is most accurately made by successive approximations based on detailed sequential analysis, with first approximations based on a simplified procedure.

b. One simplified method for solving the problem of two simultaneous supplies at different shortage frequencies is based upon the following equations:

$$TRY = YRA + YRB \quad (1)$$

$$CY = CYB + (CYA - CYB)(YRA/TRY) \quad (2)$$

$$CS = CYRAA - CYRAB \quad (3)$$

Where TRY = Total required yield

CY = Storage required for simultaneous supply at different frequencies

CS = Cutoff storage below which water will not be supplied for less severe criteria

YRA = Yield required for the more severe shortage criteria

YRB = Yield required for the less severe shortage criteria

CYB = Storage required to supply total required yield (TRY) at the less severe shortage criteria

CYA = Storage required to supply total required yield (TRY) at the more severe shortage criteria

CYRAA = Storage required for yield YRA at more severe shortage criteria and

CYRAB = Storage required for yield YRA at less severe shortage criteria.

c. The use of equations (1), (2) and (3) is illustrated in the following example:

Problem: Find the storage required to yield 49 cfs at a 1% chance of shortage and 12.5 cfs at a 10% chance of shortage. Use storage-yield curves for 1% and 10% chance of shortage as shown on Plate 12.

Solution: More severe shortage criterion = 1% chance of shortage per year
Less severe shortage criterion = 10% chance of shortage per year

YRA = 49 cfs

YRB = 12.5 cfs

From Equation (1):

TRY = 49 + 12.5 = 61.5 cfs

From Plate 12:

CYA = 84,500 acre-feet (curve b @ 61.5 cfs)

CYB = 34,700 acre-feet (curve d @ 61.5 cfs)

CYRAA = 59,400 acre-feet (curve b @ 49 cfs)

CYRAB = 24,000 acre-feet (curve d @ 49 cfs)

From Equation (2):

$$\begin{aligned} CY &= 34{,}700 + (84{,}500 - 34{,}700)(49/61.5) \\ &= 34{,}700 + (49{,}800)(.79674) = 34{,}700 + 39{,}700 \\ &= 74{,}400 \text{ acre-feet} \end{aligned}$$

From Equation (3):

$$CS = 59{,}400 - 24{,}000 = 35{,}400 \text{ acre-feet}$$

d. The simplified method indicates that storage of 74,400 acre-feet will be required to supply both demands at the given shortage criteria that releases for the lower-priority purpose (10% chance of shortage) should be stopped when the storage is reduced to 35,400 acre-feet in order to maintain releases for the higher-priority purpose (1% chance of shortage).

12. ROLE OF STREAMFLOW SIMULATION

Streamflow simulation is used to supplement drought data of record by providing the designer with different ways in which droughts might occur in the future. The droughts of record have little probability of recurring exactly as recorded. One way of obtaining different sequences of inflows would be to rearrange the monthly flows at random. This might be appropriate if there were no seasonal flow variations or serial correlation of the current flow and the preceding flow. Even so, this procedure would not change the magnitudes of the flows, but only their sequence. By the use of a multiple regression model, a streamflow simulator such as the one described in reference 16 can be used to construct many ways in which the monthly flows can occur, maintaining proper seasonal variations and persistence characteristics. Use of simulated streamflows will prevent operational plans from being "tailor made" to the drought of record. Sampling errors of the statistics (mean, standard deviation, skew and correlation coefficients) based on the recorded flows, limit the reliability of the simulated flows. Even so, a more realistic and dependable storage requirement can be obtained by routing the simulated flows and the flows of record through the reservoir project under the various proposed plans of operation.

13. COMPUTATION AIDS

The judicious use of computation aids can greatly reduce the time required to complete a sequential routing study by conventional manual methods. Several useful computation aids are discussed in Appendix 6.

14. BIBLIOGRAPHY

Publications of particular importance on the subject of storage-yield are listed in Appendix 7.

LOW FLOW REGULATION BY RESERVOIRS

1 OBJECTIVES OF LOW FLOW REGULATION

- 1.1 WATER SUPPLY (For Withdrawal Downstream)
  - (a) Municipal & Industrial Supplies
  - (b) Agricultural (Irrigation)
  - (c) Reduction of Water Supply Intake Problems and Pumping
- 1.2 WATER TEMPERATURE & DISSOLVED OXYGEN CONTROL
  - (a) Cooling Water for Industries
  - (b) Fish and Wildlife Benefits
  - (c) Biological Effects
  - (d) Ice Control in Rivers
- 1.3 DILUTION OF CONTAMINANTS (Not as Substitute for Waste Treatment)
  - (a) Reduction of Salinity Concentrations (ppm)
  - (b) Reductions in Concentrations of Wastes (Sewage)
  - (c) Reduction of Odors
- 1.4 BENEFICIAL INCREASE IN STAGES
  - (a) Navigation (Maintenance of Minimum Stages and Reduction of Dredging)
  - (b) Stabilization of Stages for Docks and Other Structures
  - (c) Run-of-River Hydropower Production

2 AGENCIES CONCERNED WITH LOW FLOW REGULATION

- 2.1 DEPARTMENT OF THE INTERIOR
  - (a) FWPCA
  - (b) Fish & Wildlife Service
  - (c) USGS (Gaging)
  - (d) Power Administrators
  - (e) National Park Service
- 2.2 OTHER FEDERAL AGENCIES
  - (a) Atomic Energy Commission
  - (b) Federal Power Commission
  - (c) USWB (ESSA)
- 2.3 DEPARTMENT OF HEW
  - Public Health Service
- 2.4 DEPARTMENT OF THE ARMY
  - (a) Corps of Engineers (CW)
  - (b) Corps of Engineers (Military)
- 2.5 STATES AND MUNICIPALITIES
  - (a) Health & Recreation Agencies
  - (b) Fish & Wildlife Agencies
  - (c) Water Resources Agencies
  - (d) Port Authorities
  - (e) Interstate Compact Commission

3 PHASES OF TECHNICAL ACTIVITIES RELATING TO LOW FLOW REGULATION

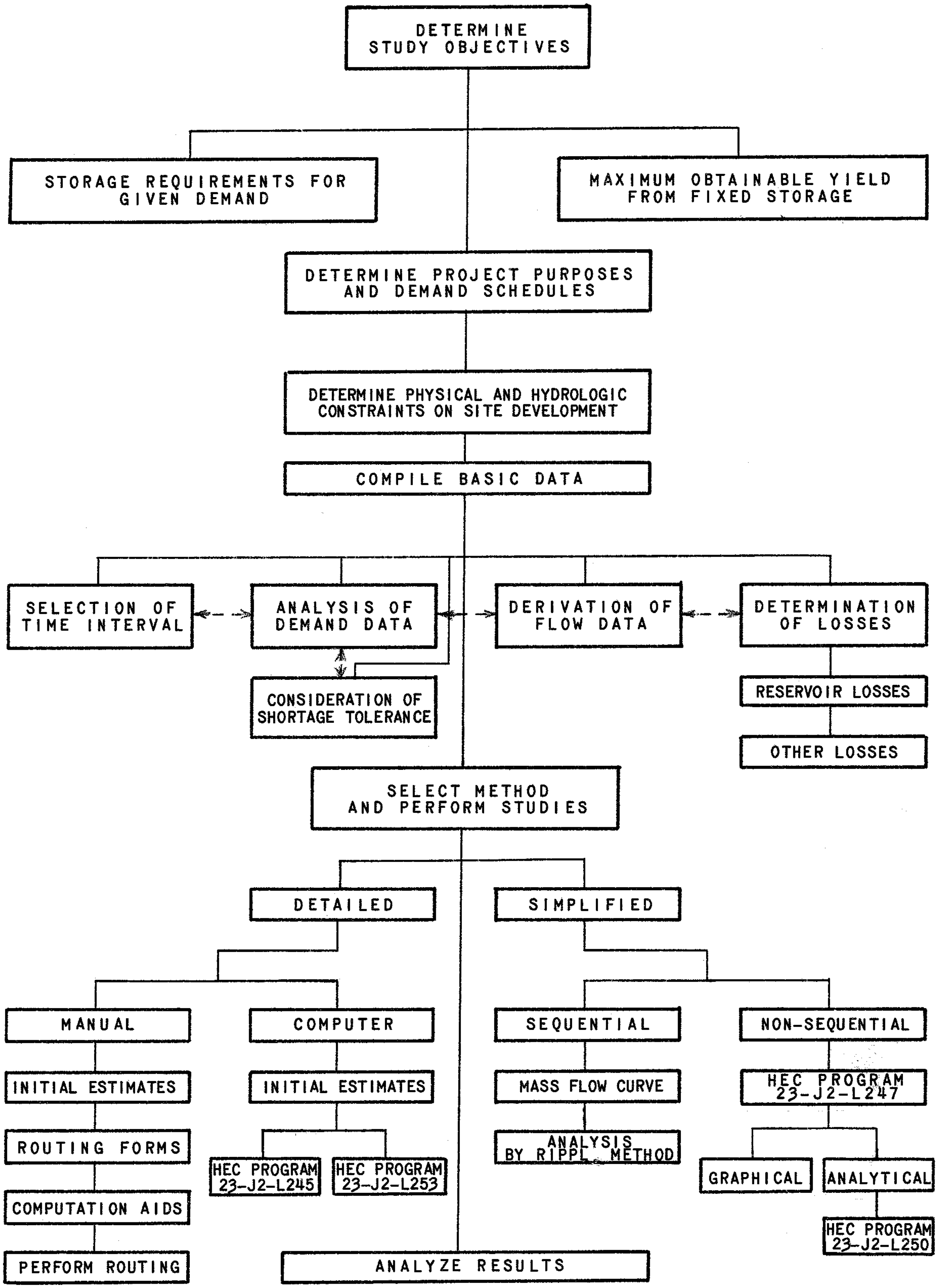
- 3.1 DATA COLLECTION & BASIC ANALYSIS
  - (a) Measurements of Flow and Water Quality Characteristics in Streams
  - (b) Measurements of Water Quality Characteristics in Reservoirs
  - (c) Measurements of Currents and Water Quality in Large Lakes
  - (d) Measurements of Waste Inflows to Streams and Lakes
  - (e) Measurements of Ground Water
- 3.2 PLANNING AND DESIGN OF FACILITIES
  - (a) Determination of Functional Objectives and Standards
  - (b) Determinations of Reservoir Storage Requirements and Systems Plan
  - (c) Design of Facilities & Basic Operating Instructions
  - (d) Project Benefit Evaluations
  - (e) Provisions for Control of Sediment Inflow into Streams During Construction Operations
- 3.3 RESERVOIR REGULATION
  - (a) Special Measurements of Water Quality Characteristics in Reservoirs
  - (b) Special Measurements of Water Quality at Key Locations Downstream from Reservoirs
  - (c) Improvement of Reg Plan for Water Quality Operation of Existing Reservoirs Under Existing Authorizations
  - (d) Coordination of Daily Reservoir Operation with Others Concerned; Existing Projects
  - (e) Determination of Water Quality Provisions of Regulation Plans for Res under New Authorizations
- 3.4 RESEARCH AND INVESTIGATIONS
  - (a) Chemical Constituents of Water Quality
  - (b) Biological Aspects of Water Quality
  - (c) Methods and Devices for Measuring Water Quality Characteristics
  - (d) Ground Water in Relation to Quality of Surface Flow
  - (e) Water Characteristics, Stratifications and Movement in Reservoirs; Analytical and Field Investigations
  - (f) Water Quality in Great Lakes and Hydraulic Factors
  - (g) Research on Design of Regulation Facilities

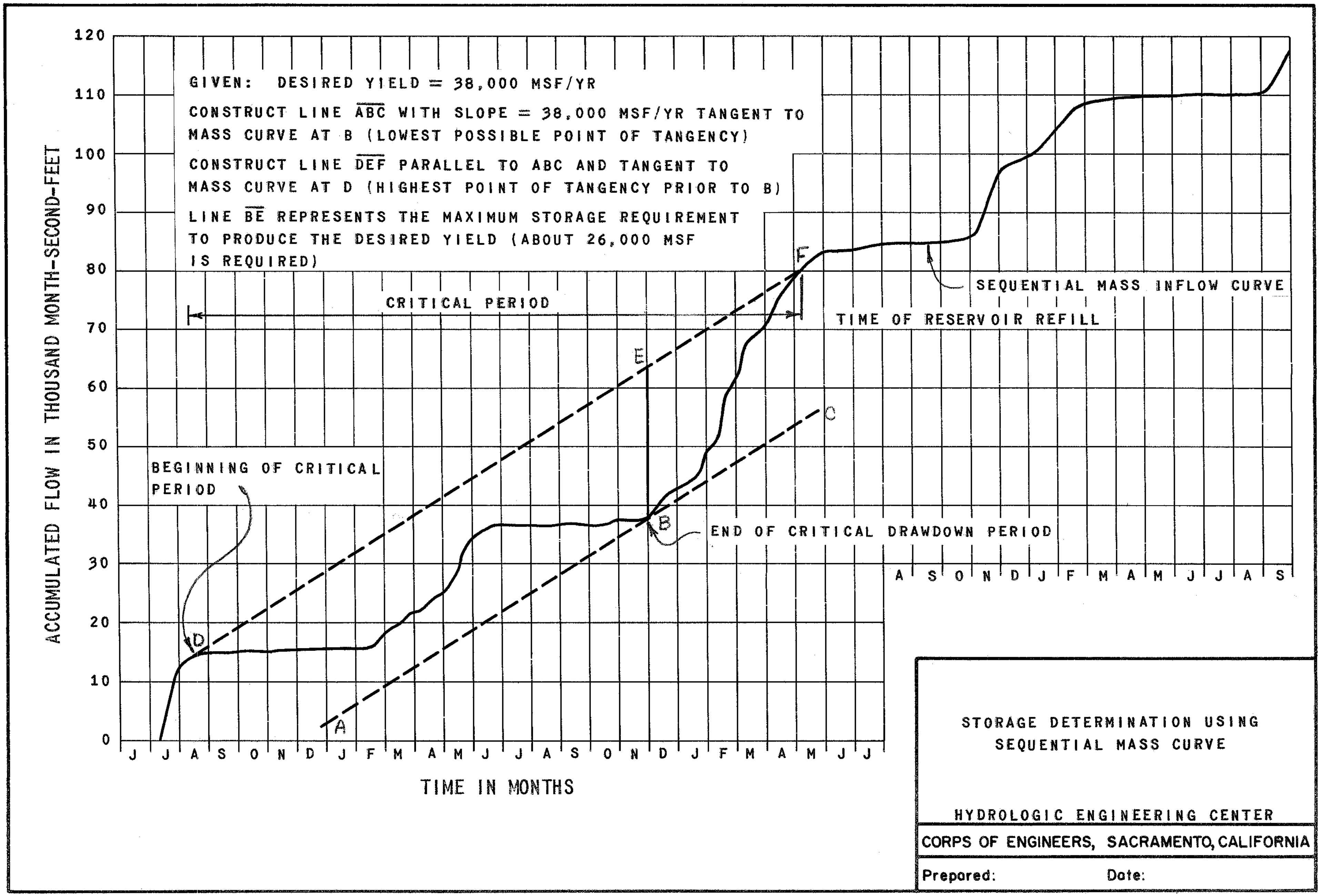
4 MANAGEMENT ACTIVITIES INVOLVED IN LOW FLOW REGULATION

- 4.1 ADMINISTRATION OF INVESTIGATIONS, STUDIES, AND REPORTS
  - (a) Authorizations
  - (b) Budgeting
  - (c) Programming
  - (d) Coordination of Preparation, Reviews and Processing
- 4.2 ESTABLISHING STANDARDS, CRITERIA, POLICIES, & GUIDE LINES
  - (a) Water Quality Standards for Health
  - (b) Salinity Standards for Water Supplies
  - (c) Deficiency Limits (Permissible Shortages)
  - (d) Benefit Evaluations, Policies and Criteria
- 4.3 COORDINATION OF PROJECT OPERATIONS
  - (a) Development of Regulations for Low Flow Operation of Reservoirs
  - (b) Interagency Reservoir Systems Operations (In Practice)
  - (c) Contracts and Financial Arrangements
  - (d) Monitoring of Water Quality Operations
- 4.4 EDUCATION AND TRAINING
  - (a) Technical Personnel Training (Special Areas)
  - (b) Public Information Services Re Water Quality
  - (c) Seminars and Technical Meetings Re Water Quality

PLATE 1

DETERMINATION OF RESERVOIR STORAGE REQUIREMENTS AND FIRM YIELD




GIVEN: DESIRED YIELD = 38,000 MSF/YR
CONSTRUCT LINE $\overline{ABC}$ WITH SLOPE = 38,000 MSF/YR TANGENT TO MASS CURVE AT B (LOWEST POSSIBLE POINT OF TANGENCY)
CONSTRUCT LINE $\overline{DEF}$ PARALLEL TO ABC AND TANGENT TO MASS CURVE AT D (HIGHEST POINT OF TANGENCY PRIOR TO B)
LINE $\overline{BE}$ REPRESENTS THE MAXIMUM STORAGE REQUIREMENT TO PRODUCE THE DESIRED YIELD (ABOUT 26,000 MSF IS REQUIRED)
CRITICAL PERIOD
TIME OF RESERVOIR REFILL
SEQUENTIAL MASS INFLOW CURVE
BEGINNING OF CRITICAL PERIOD
END OF CRITICAL DRAWDOWN PERIOD
A
B
C
D
E
F
ACCUMULATED FLOW IN THOUSAND MONTH-SECOND-FEET
120
110
100
90
80
70
60
50
40
30
20
10
0
J J A S O N D J F M A M J J A S O N D J F M A M J J
A S O N D J F M A M J J A S
TIME IN MONTHS
STORAGE DETERMINATION USING SEQUENTIAL MASS CURVE
HYDROLOGIC ENGINEERING CENTER
CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA
Prepared:
Date:

SAMPLE COMPUTATION-INDEPENDENT LOW-FLOW EVENTS
PARTIAL DURATION-6-MONTH VOLUMES

YEAR	MONTH	FLOW (MSF)	6-MONTH VOLUME (MSF)	RANK	YEAR	MONTH	FLOW (MSF)	6-MONTH VOLUME (MSF)	RANK
1958	Jan	728	728*		1962	Jan	1176	1827	
	Feb	1381	2109*			Feb	2075	3749	
	Mar	2482	4591*			Mar	2302	5910	
	Apr	1643	6234*			Apr	1767	7558	
	May	714	6948*			May	1235	8698	
	Jun	308	7256			Jun	526	9081	
	Jul	166	6694	**		Jul	191	8096	**
	Aug	155	5468	**		Aug	149	6170	**
	Sep	108	3094	**		Sep	109	3977	**
	Oct	92	1543	**		Oct	84	2294	**
	Nov	66	895	**		Nov	66	1125	**
	Dec	112	699	3		Dec	98	697	2
1959	Jan	1581	2114	**	1963	Jan	1306	1812	**
	Feb	1774	3733	**		Feb	1666	3329	**
	Mar	1563	5188	**		Mar	2351	5571	**
	Apr	1733	6829	**		Apr	1940	7427	**
	May	1088	7851	**		May	923	8284	**
	Jun	470	8209			Jun	412	8598	
	Jul	229	6857			Jul	161	7453	
	Aug	153	5236			Aug	120	5907	
	Sep	123	3796			Sep	123	3679	
	Oct	100	2163			Oct	119	1858	
	Nov	97	1172			Nov	134	1069	
	Dec	165	867			Dec	235	892	
1960	Jan	1382	2020		1964	Jan	1660	2391	
	Feb	2049	3916			Feb	1598	3869	
	Mar	1996	5789			Mar	1785	5531	
	Apr	1959	7648			Apr	1936	7348	
	May	1448	8999			May	910	8124	
	Jun	565	9399			Jun	348	8237	
	Jul	224	8241			Jul	163	6740	**
	Aug	137	6329			Aug	100	5242	**
	Sep	110	4443			Sep	96	3553	**
	Oct	94	2578			Oct	82	1699	**
	Nov	65	1195			Nov	89	878	**
	Dec	110	740			Dec	141	671	1
1961	Jan	1001	1517		1965	Jan	905	1413	**
	Feb	2389	3769			Feb	2699	4012	**
	Mar	1995	5654			Mar	1996	5912	**
	Apr	1954	7514			Apr	1870	7700	**
	May	1292	8741			May	1076	8687	**
	Jun	459	9090			Jun	365	8911	
	Jul	250	8339			Jul	173	8179	**
	Aug	153	6103			Aug	107	5587	**
	Sep	141	4249			Sep	95	3686	**
	Oct	119	2414			Oct	84	1900	**
	Nov	95	1217			Nov	80	904	**
	Dec	143	901			Dec	182	721	4

*Not considered because volume is not a 6-month volume.
**Not considered after selection of the numbered volume in order to assure independence of subsequent selections.

RANK	6-MONTH VOLUME (MSF)	PLOTTING POSITION (PERCENT)
1	671	8.72
2	697	21.27
3	699	33.82
4	721	46.37

Duration = 6 months
No. of months eliminated (*) because of incomplete volume = Duration - 1
$= 6 - 1 = 5$
Length of record = 8 yrs.
Effective record =
8 years-5 months = 7.58 years
Plotting position of lowest 6-month volume (from Equation 1, "Statistical Methods in Hydrology")
$= 1 - (.5)^{1/7.58}$
$= 1 - .9128 = .0872$
or 8.72 percent
$\Delta P = .9128 - .0872 = .8256$
$\Delta I = 7.58 - 1 = 6.58$
$\Delta R = \text{Rank} - 1$

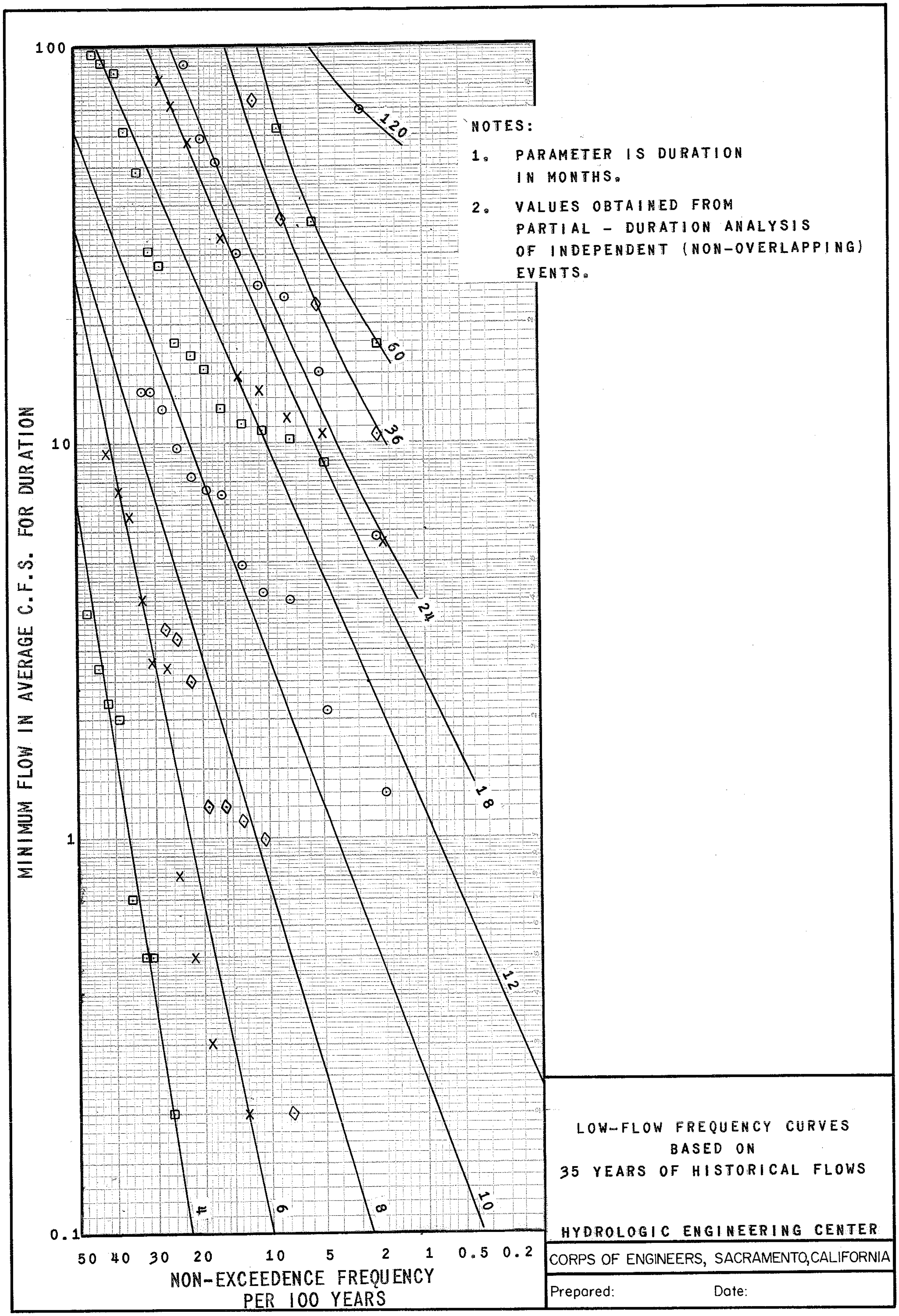
Formula for plotting position of volumes other than the lowest volume

$$PP = .0872 + (\Delta R)\left(\frac{\Delta P}{\Delta I}\right)$$

NOTE: The number of events to be ranked is limited to the smaller of the two limits as shown below:

(1) N = No. of months in rec.
n = No. of months in dur.
Limit 1 = $N/n = 8 \times 12/6 = 96/6 = 16$

(2) Limit 2 = R
where R is the rank of the last event with plotting position less than 50% (In this example R = 4)

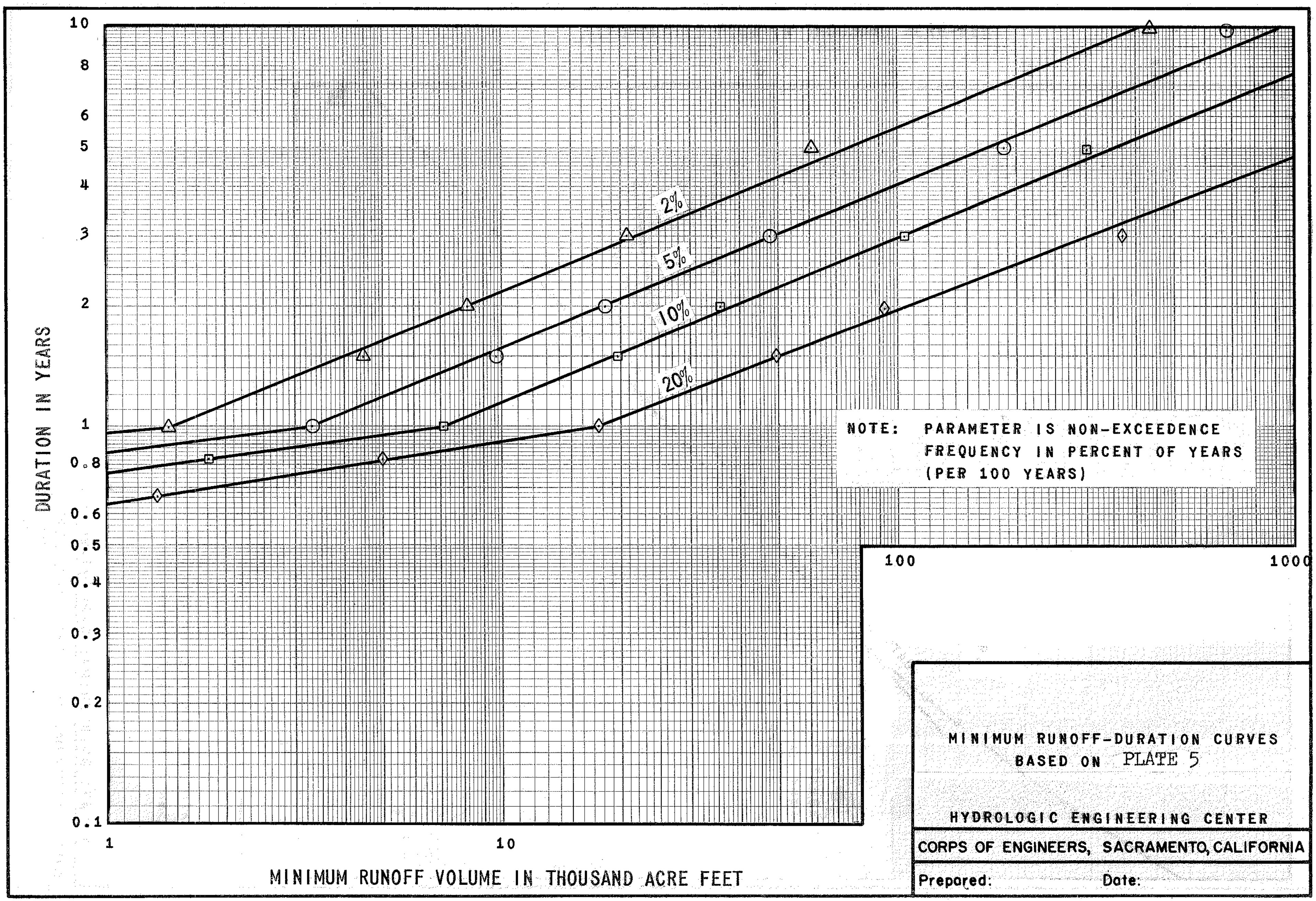


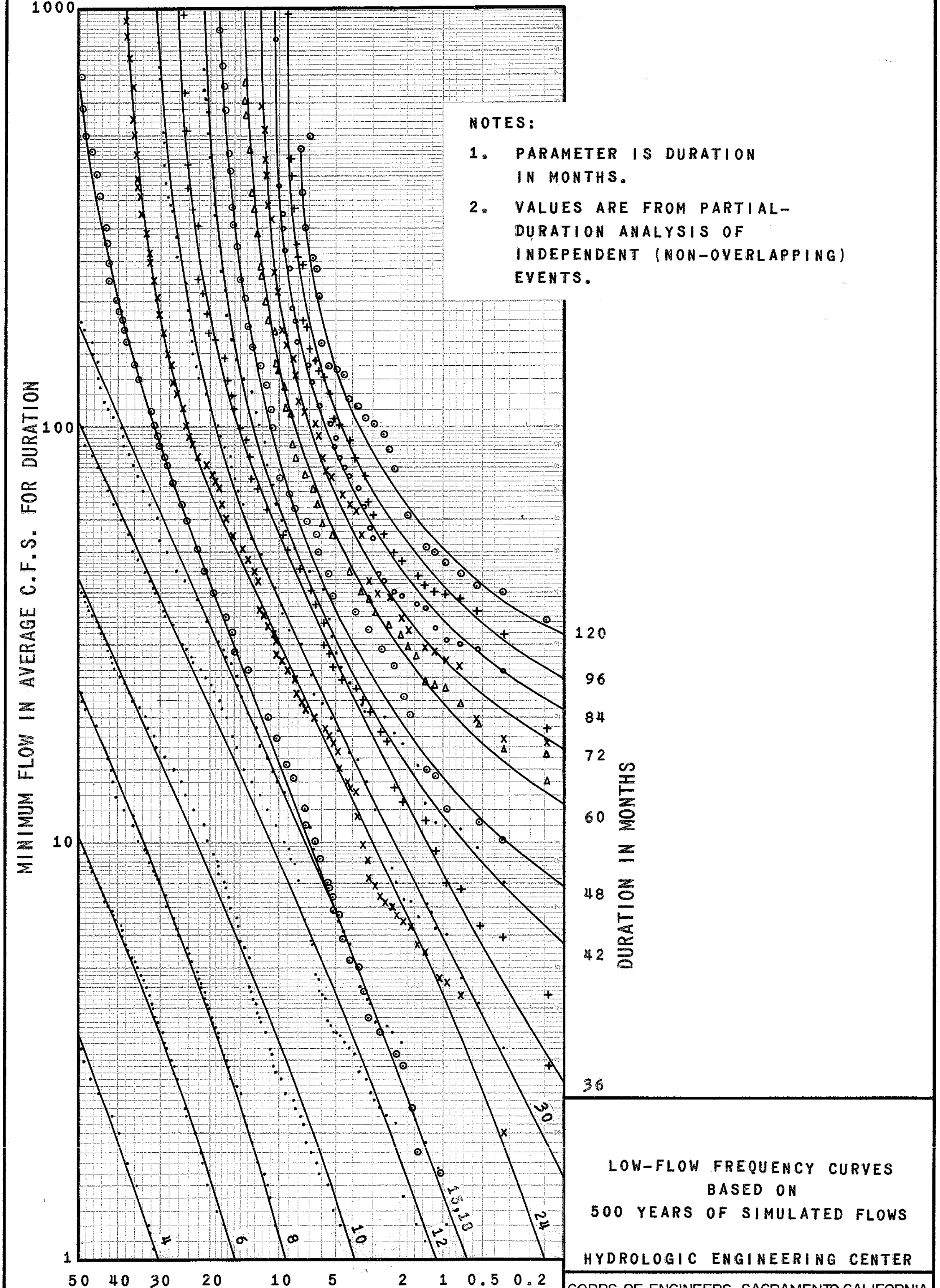
LOW-FLOW FREQUENCY CURVES
BASED ON
35 YEARS OF HISTORICAL FLOWS

HYDROLOGIC ENGINEERING CENTER

CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA

Prepared: Date:


10
8
6
5
4
3
2
1
0.8
0.6
0.5
0.4
0.3
0.2
0.1
DURATION IN YEARS
1
10
100
1000
MINIMUM RUNOFF VOLUME IN THOUSAND ACRE FEET
2%
5%
10%
20%
NOTE: PARAMETER IS NON-EXCEEDENCE FREQUENCY IN PERCENT OF YEARS (PER 100 YEARS)
MINIMUM RUNOFF-DURATION CURVES
BASED ON PLATE 5
HYDROLOGIC ENGINEERING CENTER
CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA
Prepared:
Date:



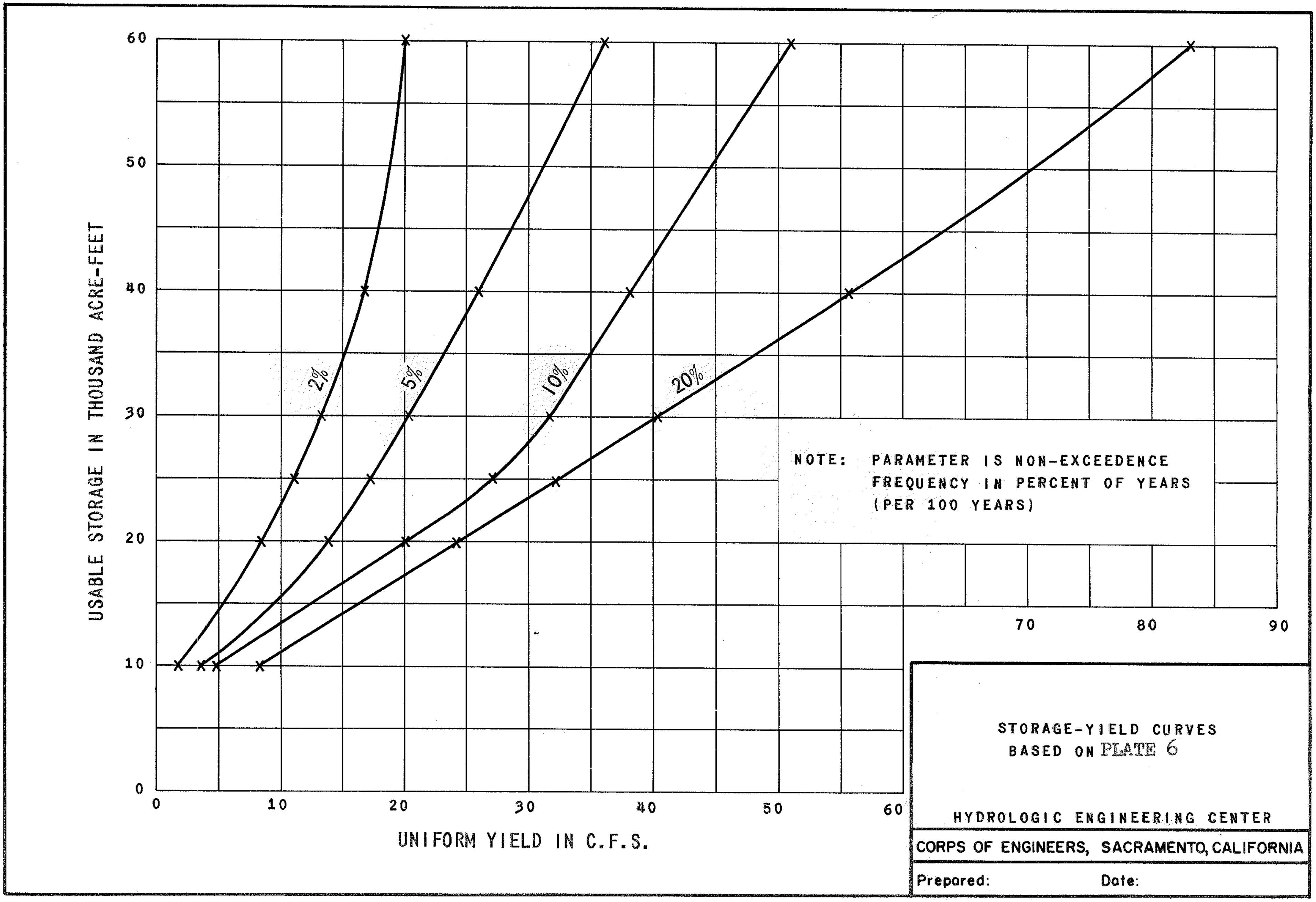
LOW-FLOW FREQUENCY CURVES
BASED ON
500 YEARS OF SIMULATED FLOWS

HYDROLOGIC ENGINEERING CENTER

CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA

Prepared: Date:

PLATE 8


60
50
40
30
20
10
0
USABLE STORAGE IN THOUSAND ACRE-FEET
0
10
20
30
40
50
60
70
80
90
UNIFORM YIELD IN C.F.S.
2%
5%
10%
20%
NOTE: PARAMETER IS NON-EXCEEDENCE FREQUENCY IN PERCENT OF YEARS (PER 100 YEARS)
STORAGE-YIELD CURVES
BASED ON PLATE 6
HYDROLOGIC ENGINEERING CENTER
CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA
Prepared:
Date:

SAMPLE MULTIPLE PURPOSE ROUTING

Column Description (See Program Description 23-J2-L245 for definition of computer variable names shown in caps)

Col 1. Date of routing period (month number/year)

Col 2. Number of days in routing period (NDAYS). Normally an average of 30.4 days per period would be used and this column would be eliminated.

Col 3. Factor used to convert average flow in cfs to acre-feet for the period (Col 2 times 1.9835). Normally omitted using an average period length of 30.4 days.

*Col 4. Average inflow to reservoir in cfs.

Col 5. Average reservoir release to channel in cfs. The controlling requirement is the larger of columns 19, 22, 27, or 31 unless reservoir evacuation for flood control is greater.

Col 6. Average change in storage for period (±) in cfs which is the algebraic sum of columns 4, 5, 17 and 18.

Col 7. Change in storage in acre-feet which is col 6 times col 3.

Col 8. End of period storage in acre-feet which is previous periods storage in column 8 + column 7.

*Col 9. Maximum allowable conservation storage for the period in acre-feet (FULRS). This column can be omitted if storage is constant during year.

*Col 10. Quality of reservoir inflow normally in parts per million (QUALI)

Col 11. The quality of the reservoir contents in PPM is normally determined by assuming complete mixing as follows:

$$\frac{(\mathrm{STOR1})\ (\mathrm{QUR}) + (\mathrm{QI})\ (\mathrm{QUALI})\ (\mathrm{Col.}\ 3)}{(\mathrm{STOR1}) + (\mathrm{QI})\ (\mathrm{Col.}\ 3) - (\mathrm{Col.}\ 16)}$$

Storage from previous period is used for STOR1

Col 12. Estimated average storage for period which is used to compute evaporation and power head. Normally the end of previous period storage is used, although this introduces a cumulative error.

*Furnished from basic data

Col 13. Pool elevation in feet corresponding to estimated storage of Col 12.

Col 14. Reservoir area in acres (AREA) corresponding to estimated storage.

*Col 15. Net reservoir evaporation (EVAP) in inches

Col 16. Total reservoir evaporation in acre-feet determined as follows:

$$\frac{(AREA)(EVAP)}{12}$$

This column normally omitted since evaporation can be determined in cfs. This column is shown so that computer program evaporation can be readily compared.

Col 17. Total reservoir evaporation in cfs which is col 16/col 3.

*Col 18. Reservoir release to pipeline in cfs (QOMN2) to draw water directly out of reservoir and bypass the power penstock.

*Col 19. Required release to channel below the dam in cfs (QDMIN) which can pass through penstock.

*Col 20. Power requirement in 1,000 kw-hr (POWR).

Col 21. Power head in feet which is (column 13) - (tailwater elevation) - (head loss). Block loading tailwater is normally used depending on intended operation.

Col 22. Required reservoir release to satisfy the power requirement determined as follows:

$$\frac{(0.492)\ (POWR)\ (X10^3)}{(EFFCY)\ (Col.\ 21)\ (Col.\ 2)}$$

*Col 23. Tributary flow below the dam and above the downstream control point in cfs (QL)

*Col 24. Quality of tributary flow in units corresponding to col 10 units. (QUALL).

*Col 25. Effluent at downstream control point in tons per day (EFLNT).

*Col 26. Maximum allowable quality concentration at the downstream control point in units corresponding to col 10 units (QUALD).

*Furnished from basic data

Col 27. Required reservoir release to maintain quality standards at the downstream control point determined as follows:

$$\frac{(ALOS)\ (QUALD\text{-}QUR)\ (1\text{-}CLOSS) + (QL)\ (QUALL\text{-}QUALD) + (EFLNT)}{(QUALD\text{-}QUR)\ (1\text{-}CLOSS)}$$

*Col 28. Required flow at downstream control point in cfs to satisfy water rights (QRITS).

*Col 29. Flow required at downstream control points in addition to water rights.

*Col 30. Constant channel loss in cfs below reservoir (ALOS).

Col 31. Required reservoir release in cfs to satisfy total downstream flow requirements determined as follows:

$$\frac{(ALOS)\ (1\text{-}CLOSS) + QRITS + QDMIN - QL}{(1 - CLOSS)}$$

Col 32. Resulting flow in cfs at downstream control point determined as follows:

$$QL + ((Col.\ 5) - ALOS)\ (1\text{-}CLOSS)$$

Col 33. Actual resulting quality in units corresponding to Col 10 at downstream control point determined as follows:

$$\frac{(QUR)\ ((Col\ 5) - ALOS)(1\text{-}CLOSS) + (QL)(QUALL) + (371)(EFLNT)}{(Col\ 32)}$$

Col 34. Actual resulting power generated in kw-hrs ($X10^3$) determined as follows:

(Col 5)(Col 21) (EFFCY)(2.033)(NDALYS) up to the maximum power

Where maximum power is:

(PWRMX)(OVLOD)(24)(NDAYS)

Col 35. Any special remarks.

Col 36. Controlling case defined as follows:

1. Release restricted by reservoir outlet capacity.
2. " " " damsite channel capacity.
3. " " " downstream channel capacity.
4. " to satisfy downstream water requirement.
5. Release to satisfy water requirements at dam.
6. Release to satisfy power requirements.
7. Release to satisfy quality requirements.

*Furnished from basic data

8. Release required to prevent over filling flood control storage.
9. Release controlled by declared shortage.
10. Release restricted by bottom of conservation pool.
11. Release to empty flood control storage.

Clinton Reservoir
Example Problem Routing

Plate 10

PWRMX = 500 KW
OVLOD = 1.15
EFFCY = 0.86
CLOSS = 0.05
TLWEL = 840 ft.
QCAP = 2000 cfs

Max. Downstream Channel Capacity
Oct. - Apr. = 90,000 cfs
May - Sept. = 85,000 cfs

Routing Period Data			Reservoir Regulation						Reservoir Quality	
Col. 1	2	3	4	5	6	7	8	9	10	11
Date (Mo/Yr)	N DAYS (No. of days)	flow conv. factor (1.9835) (2)	QI (Res. inflow in cfs)	(Res. Release in cfs)	Δstor. 4 − 5 − 17 − 18 (cfs)	Δstor. (6)(3) (A.F.)	E.O.P. stor. (P 8 + 7) (A.F.)	Max. Consv. Stor. Allow ($\times 10^3$ A.F.)	(Qual. Inflow in PPM)	(Qual. Res. Incl. Release in PPM)
	INPUT		INPUT					INPUT	INPUT	
9/50							180,000			100
10/50	31	61.487	106	406	− 325	−20,000	160,000	160	129	101
11/50	30	59.504	14	50	− 61	− 3,630	156,370	160	197	101
12/50	31	61.487	12	25	− 37	− 2,275	154,095	160	199	101
1/51	31	61.487	13	25	− 36	− 2,214	151,881	170	198	102
2/51	28	55.537	26	13	− 13	− 722	151,159	180	186	103
3/51	31	61.487	47	13	+ 11	+ 676	151,835	180	171	104
4/51	30	59.504	84	15	+ 40	+ 2,380	154,215	180	142	105
5/51	31	61.487	406	78	+ 297	+18,262	172,477	180	96	104
6/51	30	59.504	1,610	1,440	+ 126	+ 7,523	180,000	180	28	77
7/51	31	61.487	3,142	2,000*	+1,096	+67,390	247,390	180	24	50
8/51	31	61.487	61	1,111	−1,096	−67,390	180,000	180	160	52
9/51	30	59.504	611	569	0	0	180,000	180	73	55

INPUT refers to data determined prior to routing
Integer in formulas refer to column numbers

$$11 = \frac{(P\,8)(P\,11) + (4)(10)(3)}{(P\,8) + (3)(4) - (16)}$$

Clinton Reservoir
Example Problem Routing

Plate 10 - continued

Approximations			Evaporation			Water Req'd. at Dam		Power Requirement		
12	13	14	15	16	17	18	19	20	21	22
Est. Ave. Store ($\times 10^3$ A.F.)	Elev. (ft)	Area (Ac)	Net Evap. (in)	Evap. (14)(15) ÷ 12 (A.F.)	Evap. 16 ÷ 3 (cfs)	(Req'd Pipe Release in CFS)	(Req'd River Release in CFS)	Req'd Power ($\times 10^3$ Kw-Hr)	Head (13 - TLWEL) (ft)	(Req'd Release for Power in cfs)
			INPUT			INPUT	INPUT	INPUT		
170	881.0	8,008	2	1,334	22	3	25	26	41.0	12
159	879.5	7,732	2	1,290	22	3	25	25	39.5	12
155	879.0	7,641	2	1,272	21	3	25	45	39.0	21
153	878.7	7,586	2	1,264	21	3	25	45	38.7	21
152	878.0	7,568	2	1,261	23	3	10	24	38.0	13
152	878.0	7,568	2	1,261	20	3	10	26	38.0	13
154	878.9	7,623	2	1,270	21	8	15	25	38.9	12
157	879.0	7,696	2	1,299	21	10	15	45	39.0	21
180	882.1	8,210	3	2,052	34	10	15	43	42.1	19
215	886.0	8,969	3	2,242	36	10	15	89	46.0	37
215	886.0	8,969	3	2,242	36	10	15	89	46.0	37
180	882.1	8,210	3	2,052	34	8	10	43	42.1	19

$$22 = \frac{(0.492)\ (20) \times 10^3}{(\text{EFFCY})(\ 21\ )(\ 2\ )}$$

Clinton Reservoir
Example Problem Routing

Plate 10 - continued

Quality Required Downstream					Flow Required Downstream			
23	24	25	26	27	28	29	30	31
QL (Local flow in cfs)	Qual. of local flow	EFLNT	Max. Allow D.S. Qual.	Req'd Release for D.S. Qual.	Req'd Wtr. RTS.	Req'd Add. D.S. flow	ALOS Const. Chan. loss	Req'd Release for D.S. flow
	(PPM)	(tons/day)	(PPM)	(cfs)	(cfs)	(cfs)	(cfs)	(cfs)
INPUT	INPUT	INPUT	INPUT		INPUT	INPUT	INPUT	
50	300	2	250	33	10	40	10	10
46	356	2	250	50	10	50	10	26
309	200	2	250	0	10	50	10	0
266	200	2	250	0	10	40	10	0
302	200	2	250	0	10	70	10	0
565	200	2	250	0	10	80	10	0
756	200	4	250	0	50	90	15	0
100	200	4	250	0	50	110	15	78
788	200	4	200	0	50	220	15	0
133	200	4	200	0	50	160	15	96
233	200	4	200	0	50	80	15	0
446	200	4	200	0	50	60	15	0

$$27 = \frac{(30)(26 - 11)(1\text{-CLOSS}) + (23)(24 - 26) + (371.)(25)}{(26 - 11)(1\text{-CLOSS})}$$

$$31 = \frac{(30)(1\text{-CLOSS}) + (28) + (29) - (23)}{1\text{-CLOSS}}$$

Clinton Reservoir
Example Problem Routing

Plate 10 - continued

* Maximum Allowable

Accomplishments				
32	33	34	35	36
Act. D.S. flow (cfs)	Act. D.S. Qual. (PPM)	Act. Gen. PWR. ($\times 10^3$ Kw-Hr)	Remarks	Case
426	126	428 *		11
84	250 *	101		7
323	198	53		5
280	148	52		5
305	202	24		6
568	201	26		6
756	202	31		5
160	173	165		4
2,142	123	414 *		11
2,019	61	428 *		1
1,274	80	428 *		11
972	123	414 *		11

32 = (23) + ((5) - (30))(1-CLOSS)

$$33 = \frac{(11)((5) - (30))(1-\text{CLOSS}) + (23)(24) + (371.0)(25)}{(32)}$$

34 = (5)(21)(EFFCY)(2.033)(2)... Up to Max. Kw - Hr

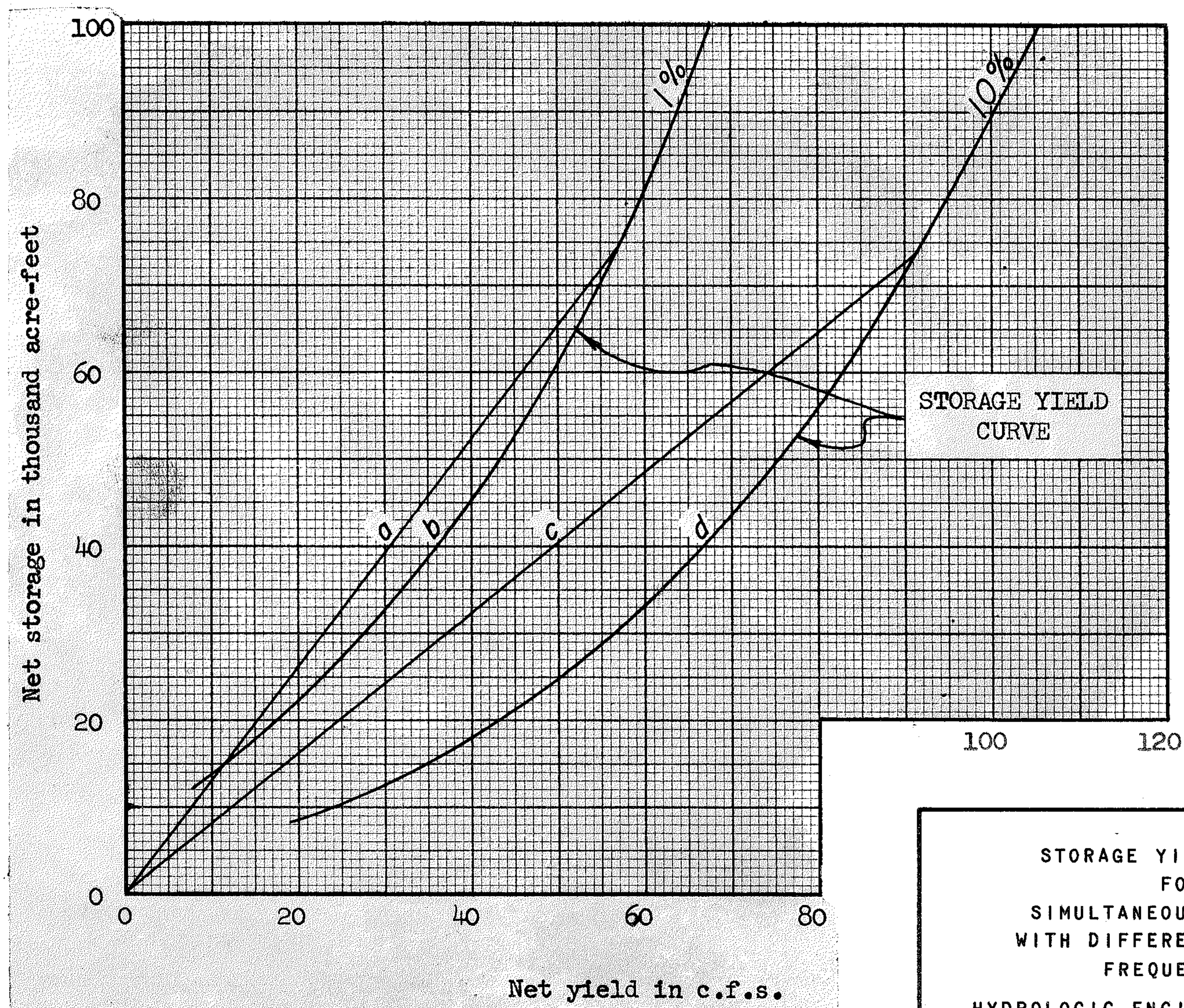
Where:

Max. Kw - Hr = (PWRMX)(OVLOD)(24.0)(2)

TYPICAL SEQUENTIAL ROUTING EXAMPLE

Month and Year	Inflow MSF	Pipeline MSF	Net Evaporation IN.	Net Evaporation MSF	Release MSF	End of Period Area ACRES	End of Period Storage MSF	End of Period Pool Elev. ft.msl	Req'd Flow@ Dam-site MSF	Actual Flow @ Damsite MSF (Maximum = 13,500)	Return Flow MSF	Local Flow MSF	Diver-sion MSF	Desired Flow @ Control MSF	Req'd Flow @ Control MSF	Actual Flow @ Control MSF (Maximum = 27,000)
INITIAL						45,440	50,521	654.0								
'53 Mar	14,210	5	-.73	-45	13,500	45,953	51,271	655.0	500	13,500	4	9,226	0	4,000	1,000	22,730
Apr	12,189	6	1.67	108	11,142	46,567	52,204	656.2		11,142	4	15,854	0	4,000	1,000	27,000
May	11,202	10	.95	59	12,816	45,440	50,521	654.0		12,816	8	11,018	0	4,500	2,000	23,842
Jun	1,075	12	5.87	369	2,346	44,314	48,869	651.8		2,346	9	2,445	300	4,500	3,000	4,500
Jul	1,088	10	4.19	245	4,237	41,902	45,465	647.0		4,237	8	1,405	650	5,000	3,000	5,000
Aug	339	9	4.88	266	4,903	38,485	40,626	639.8		4,903	7	1,090	1000	5,000	3,000	5,000
Sep	191	4	5.45	288	2,132	36,922	38,393	636.2		2,132	3	715	750	4,500	2,100	2,100
Oct	213	3	2.13	106	500	36,635	37,997	635.5		500	2	981	250	3,000	1,000	1,233
Nov	226	3	.53	27	500	36,424	37,693	635.0		500	2	1,173	0	3,000	500	1,675
Dec	334	3	-.22	-11	500	36,306	37,535	634.8		500	2	1,211	0	3,000	500	1,713
'54 Jan	885	3	-3.39	-168	500	36,706	38,085	635.7		500	2	2,763	0	3,000	500	3,265
Feb	788	4	-1.21	-67	500	36,950	38,436	636.3		500	3	3,165	0	3,000	500	3,668
Mar	2,511	5	-.73	-37	734	38,255	40,245	639.2		734	4	3,262	0	4,000	1,000	4,000
Apr	3,124	6	1.67	92	500	39,996	42,771	643.1		500	4	3,586	0	4,000	1,000	4,090
May	4,286	10	.95	53	500	42,650	46,494	648.5		500	8	6,694	0	4,500	2,000	7,202
Jun	885	12	5.87	342	3,314	40,634	43,711	644.4		3,314	9	1,477	300	4,500	3,000	4,500
Jul	352	10	4.19	222	4,632	37,500	39,199	637.5		4,632	8	1,010	650	5,000	3,000	5,000
Aug	278	9	4.88	241	3,075	35,336	36,152	632.4		3,075	7	918	1000	5,000	3,000	3,000
Sep	255	4	5.45	265	1,918	34,014	34,220	629.1		1,918	3	929	750	4,500	2,100	2,100
Oct	3,044	3	2.13	101	500	35,688	36,660	633.3		500	2	1,383	250	3,000	1,000	1,635
Nov	1,723	3	.53	27	500	36,539	37,853	635.3		500	2	951	0	3,000	500	1,453
Dec	7,044	3	-.22	-12	500	41,130	44,406	645.5		500	2	3,312	0	3,000	500	3,814
'55 Jan	5,443	3	-3.39	-198	500	44,780	49,544	652.7	500	500	2	2,754	0	3,000	500	3,256
Feb	11,316	4	-1.21	-82	10,417	45,440	50,521	654.0	500	10,417	3	5,269	0	3,000	500	15,689
Totals	83,001	144		2191	80,666	(1 Mar 53 to 28 Feb 55)				80,666	108	82,591	5900			157,465
Total	54,431	128		2355	68,249	(1 Mar 53 to 30 Sep 54)				68,249	97	68,922	5650			131,618

(1) Desired flow furnished when reservoir is above top of buffer zone (Elev 636.70). Required flow furnished when reservoir is below top of buffer zone.



STORAGE YIELD CURVES
FOR
SIMULTANEOUS SUPPLIES
WITH DIFFERENT SHORTAGE
FREQUENCIES

HYDROLOGIC ENGINEERING CENTER

CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA

Prepared: Date:

APPENDIX I
EXPLANATION OF TERMS

Base-load plant. A hydroelectric plant which is designed to supply power to meet the base (continuous) load, thus having a high plant factor.

Critical duration. The length of time during which the largest volume must be released from storage in order to provide a specified yield.

Critical period. The actual period in a sequential record, either historical or simulated, which requires the largest volume from storage to provide a specified yield. The critical period is often taken as the time from beginning of storage utilization to the time that the conservation pool refills during the period when the reservoir is drawn down to its lowest level. The period from beginning of storage utilization to minimum pool level is referred to as the critical drawdown period.

Cutoff storage. The remaining active conservation storage volume at which it is desirable to discontinue releases from a reservoir for one purpose in order to assure future releases for a higher priority purpose.

Independent events. Statistically, independent events are events which do not affect the probability of occurrence of one another in a given series. The specialized case of this definition used in this manual refers to successive flow volumes for a given duration. A degree of independence is assured by selecting volume events so that no flow data is used in more than one volume event.

Natural flow. The flow resulting from natural hydrologic conditions. (Unaffected by man-made structures which would alter the natural regime).

Non-project conditions. The conditions that would be expected to exist in the future if a project were not built, also called pre-project conditions.

Non-sequential mass curve. A curve showing the relationship between various durations and minimum recorded flow volumes or minimum flow volumes with specified probabilities. The curve is developed without regard to sequential occurrences of flows and therefore the critical duration can be obtained from the curve, but the critical period cannot.

Peaking plant. A hydroelectric plant which is designed to supply power for meeting peak capacity loads. Peaking plants ordinarily have low plant factors.

Plant factor. The ratio of average hydroelectric plant output during a stated period to the plant's installed capacity.

Probability of shortage. The likelihood or chance that a shortage will occur in any given year based on sample data. (Sometimes expressed as a percentage, i.e., 10% probability of shortage indicates that there is one chance in ten that a shortage will occur in any given year.)

Project conditions. The conditions that would be expected to exist in the future if a project were built.

Recurrence frequency. The frequency per year with which an event of given magnitude can be expected to be surpassed. For example, an event with a recurrence frequency of .01 will be surpassed, on the average, once in a hundred years.

Recurrence interval. The average interval of time between values more extreme than a specified magnitude. Reciprocal of the recurrence frequency (may also be called the return period or exceedence interval or non-exceedence interval).

Routing interval. The basic time interval involved in a sequential routing (i.e., a weekly routing interval indicates that the routing will be composed of sequential periods one week in length).

Runoff. The portion of rainfall and snowmelt which runs off the surface of a drainage area and appears in surface streams.

Sequential mass curve. A curve showing the relationship between accumulated sequential flow volumes and continuous time. The curve is developed by continuously accumulating sequential flows and plotting the accumulated flow volume versus the actual time when that accumulation occurred. A sequential mass curve may be used in analysis of both historical and synthesized flow records.

Sequential routing study. A study which simulates the operation of a reservoir or system of reservoirs using historical or synthesized flow data in sequence.

Serial correlation. The correlation of an event with an event preceding it.

Shortage. A deficit in supply, often expressed as a ratio to or percentage of a specified demand or target yield for a given period such as one year, (i.e., a 20% shortage indicates that there is a deficit in supply equivalent to 20% of the demand or target yield).

Shortage index. As defined in reference 15, the sum of the squares of the annual shortages over a 100-year period, each shortage expressed as a ratio to the annual target yield.

Simulated (or synthesized) flows. Flow values which have been sequentially synthesized using the statistical characteristics of actual flow records.

Storage. The volume of water in a reservoir.

Yield. The amount or schedule of supply at one or more specified locations (usually expressed in terms of a draft rate, i.e., a yield of 120 cubic feet per second).

APPENDIX 2
THE EFFECT OF VARIOUS PURPOSES ON STORAGE-YIELD ANALYSES

a. Low Flow Regulation. The operation of a reservoir for low flow regulation at a downstream control point is difficult to evaluate without a detailed sequential routing, because the operation is highly dependent upon the flows between the reservoir and the control point. Since these flows can be subject to large variation, a yield based on long-period average intervening flows, as in some approximate methods, can be subject to considerable error. A detailed sequential routing, where some appropriate allowance is made for variations of local flows within the routing interval, will not only produce a more reliable estimate of storage requirements for a specified yield but will reduce the chance of estimating a firm yield in excess of what is practically obtainable. Ordinarily the yield and the corresponding operation of a reservoir for low-flow regulation is determined by detailed sequential routing of the critical period and several other periods of low flow but not for the entire period of flow record unless summary type information is needed for functions such as power.

b. Diversion and Return Flows. The analysis of yield for diversion and return flows is complicated by the fact that diversion requirements may vary from year to year as well as from season to season. Furthermore, the diversion requirements may be stated as a function of the natural flow and water rights rather than as a fixed amount. A third factor which often prohibits the use of simplified methods is that often diversion amounts may be reduced or eliminated when storage in the reservoir reaches a certain minimum or near-minimum amount. The effect of these three items is such that when any one of the three is important to a given reservoir analysis, the use of simplified methods must be abandoned in favor of the more detailed sequential techniques. These complications also often require that a detailed sequential analysis for the entire period of flow record be made in order to determine accurately the yield and the reservoir operation criteria. Coordination of the operation criteria for other purposes with diversion requirements may also be achieved by use of the detailed sequential analysis results.

c. Water Quality Control and Management.

(1) Inclusion of water quality control and management as a project purpose almost always dictates that sequential routing studies be used to evaluate project performance. Practically every variable under consideration in a water quality study may vary

seasonally, and furthermore, the variation may be random to the extent that it is necessary to introduce stochastic processes in order to evaluate a project's potential. Among the variables which must be considered in a water quality study are: (a) the variation in quality of the inflow; (b) the change in quality of the reservoir waters due to variations in inflow quality and evaporation from the reservoir surface; (c) the variation in quality of natural streamflow entering the stream between the reservoir and the control station; (d) the variation in effluents from treatment plants and storm drainage outfalls between the reservoir and the control station; and (e) the variation in quality requirements at the control station. Accurate evaluation of project performance must consider all of these variations which are pertinent to the problem under consideration.

(2) Furthermore, there are several quality parameters which may require study, and each parameter introduces additional variations which should be studied. For example, if temperature is an important parameter, the level of the reservoir from which released water is withdrawn should be considered in addition to the above variables. Likewise, if oxygen content is important, the effects of release through power units versus release through conduits must be evaluated.

d. Hydroelectric Power Generation.

(1) If hydroelectric power is included as a project purpose, detailed sequential routings are necessary to develop operation criteria, to coordinate power production with other project purposes, and to determine the project's power potential. As a rule, simplified methods are usable for power projects only when studies are of a preliminary nature such as screening studies or when there is evidence that there is very little likelihood of justifying power as a project purpose. Since power production is a function of both head and flow, a detailed sequential study is almost always required when the conservation storage is relatively large and the head can be expected to fluctuate erratically over a wide range.

(2) Determination of firm power or firm energy is usually based upon sequential routings over the critical period. Various operational plants are often used in an attempt to maximize power output while providing necessary commitments for other project purposes. When the optimum output is achieved, a rule curve for operation is developed. The rule curve is based upon the power output itself and upon the plan of operation followed in obtaining the maximum output. Additional sequential routings for the entire period of flow record are then made

using the rule curve developed in the critical period studies. These routings are used to coordinate power production with flood control operation and to determine the average annual potential energy available from the project.

(3) In areas of the country where hydroelectric power is used primarily for peaking purposes, it is extremely important that storage requirements be defined as accurately as possible, because the head available during a period of peak demand is important in determining the peaking capability of the project and an error in storage requirements can adversely affect the head with a resultant loss of peaking capability.

(4) Tailwater elevations are also of more importance in power studies than in studies for other conservation purposes because of the effect of head on power output. Several factors which may adversely affect the tailwater elevation at a reservoir are: (a) construction of a reregulation reservoir below the project under consideration; (b) high pool elevations at a project immediately downstream from the project under consideration; and (c) backwater effects of high flow on another stream if the project is near the confluence of two streams. If any of these conditions exist, the resultant tailwater conditions should be carefully evaluated. In many cases, an assumed "block-loading" tailwater should be used in determining the reservoir releases for the sequential reservoir routing. The "block-loading" tailwater elevation may be defined as the tailwater elevation resulting from sustained generation at the plant's rated capacity or at any reasonable fraction of rated capacity which represents the condition under which the project is expected to operate most of the time.

(5) The advent of reversible pump-turbines has enhanced the feasibility of the integral pumped storage type of hydroelectric development. In a project of this type reversible pump-turbines are included in the powerhouse along with conventional generating units, and an afterbay is constructed below the main dam to retain water for pumping at night. Sequential routing studies are definitely required in analyses of this type of development because of the need to define: (a) storage requirements in the afterbay; (b) pumping requirements and characteristics; and (c) the extent to which such a plan should be developed.

e. Imports and Exports. Much of what has been discussed in paragraph b (on diversions and return flows) also pertains to imports and exports of water among river basins. However, the import or export of water can affect any of the other purposes previously described and, in the case of power, these may also be imports and exports of energy which would affect the analysis. Usually imports and exports will vary annually as well as seasonally so that period of record sequential routings are necessary.

APPENDIX 3
GENERALIZED DEMAND DATA

a. Water Supply Requirements. Estimation of water supply requirements is necessary when expected demands have not been furnished. The demands for municipal and industrial water supply are variable from region to region and from locality to locality within a region. Factors such as climate, relative size of urban area, type of industry and amount of industry all affect water supply requirements. Examination of U.S. Geological Water Supply Paper 1812, "Public Water Supplies of the 100 Largest Cities in the United States", 1962, shows that for cities of more than 100,000 population the average municipal demand ranges from a minimum of about 60 gallons per capita per day (gpcpd) to a maximum of about 370 gpcpd. The average demand for the 100 cities was about 160 gpcpd in 1962. No definite trend relating size of city to average per capita demand was exhibited in the data for the 100 cities but other handbooks indicate that for cities of less than 100,000 population there is a relationship between population and average per capita demand. Information contained in such reports as Committee Print No. 32, "Water Supply and Demand", U.S. Senate Select Committee on National Water Resources, 1960, has been found useful in obtaining estimates of relative regional demands. The data in Tables 1 to 3 have been gathered from various handbooks and technical papers and are furnished as a guide in estimating water supply requirements.

TABLE 1

ESTIMATED MUNICIPAL AND INDUSTRIAL DEMAND

POPULATION (thousands)	LOW gpcpd	AVERAGE gpcpd	HIGH gpcpd
1	60	80	100
5	70	120	150
10	80	140	180
50	90	150	210
100 or more	100	160	230

NOTES:

(1) Average demand based on use as follows: 40% Domestic, 35% Industrial, 10% Public, and 15% Waste and Miscellaneous.

(2) Industrial requirements vary widely among industries and therefore, if it appears that industrial requirements will be relatively large, specific information concerning the industry and its needs should be obtained.

(3) It has been estimated that between 75% and 90% of the total demand is returned to streamflow via sanitary sewers and industrial waste outlets.

(4) Relative magnitude of regional demands may be estimated from the following information. However, it should be noted that this information is based primarily upon the entire geographic region and that widespread variations may occur within a given region.

New England - Average
Delaware and Hudson River Basins - Below Average
Chesapeake Bay Area - Below Average
Southeast - Low
East Great Lakes - Above Average
West Great Lakes - High
Ohio River Basin - Below Average
Cumberland River Basin - Below Average
Tennessee River Basin - Average
Upper Mississippi River Basin - Average
Lower Mississippi River Basin - Low
Upper Missouri River Basin - Below Average
Lower Missouri River Basin - Below Average
Upper Arkansas-Red River Basin - Below Average
Lower Arkansas-Red, White River Basin - Below Average
Western Gulf - Low
Upper Rio Grande and Pecos - Low
Colorado River Basin - Above Average
Great Basin - High
Pacific Northwest - High
Central Pacific - Below Average
South Pacific - Average

TABLE 2

SEASONAL VARIATION IN MUNICIPAL AND
INDUSTRIAL WATER SUPPLY DEMAND

MONTH	SMALL VARIATION	AVERAGE VARIATION	LARGE VARIATION
	(Percent of Annual Total)		
January	7	6	4
February	7	6	4
March	7	6	4
April	7	7	6
May	8	8	7
June	9	10	9
July	10	11	14
August	10	12	16
September	10	11	14
October	9	9	12
November	9	8	6
December	7	6	4
TOTAL	100	100	100

NOTE: Seasonal variation in demand is highly dependent upon climatic variations. Large climatic variations cause large demand variations particularly in arid or semi-arid regions.

TABLE 3

ESTIMATED MINIMUM DOMESTIC WATER REQUIREMENTS

PURPOSE	REQUIREMENT (gpcpd)
Bare Minimum	.25
Subsistence	2
Sanitary Needs	20
Other Domestic	10

b. Irrigation Requirements.

(1) Generalized estimates of irrigation requirements are difficult to obtain because of the variations in factors such as climatic conditions, soil types, crop patterns, and irrigation practices. All of the above factors may affect irrigation requirements for a specific locale. Therefore, any generalized estimates of requirements should, if possible, be compared with available data for the locale under consideration. In order to determine the amount of water required from storage for an irrigation project, estimates of crop requirements and losses and wastes must be made. Crop requirements are often specified as total requirements from which deductions for precipitation during the growing season must be made. Losses and waste are usually divided into conveyance losses and waste and irrigation losses and waste. Conveyance losses and waste are dependent upon the design and construction of conveyance and distribution systems as well as the operation and maintenance of the systems. Irrigation losses and waste are dependent upon slopes of the irrigated surfaces, soil conditions, preparation of irrigated surfaces, method of irrigation and the skill of the irrigator.

(2) In general, all of the above losses and waste will be larger in areas where water is relatively plentiful and smaller in areas where water is limited. The term irrigation efficiency is used to account for irrigation losses and waste and to describe the percentage of applied water actually available to a crop for growth. The irrigation efficiency is defined as the percentage of delivered water which is available in the root zone for crop growth. Many tests have been made to determine irrigation efficiencies and, although efficiencies as low as 10% have been observed, it appears that average irrigation efficiencies for common types of farm crops and orchards range between 30% and 50%. Conveyance losses are primarily due to seepage in conveyance canals and have been observed to vary from 13% to 48% of the flow in the canal. It appears that a conveyance loss of about 30% of the total diverted flow is not an unreasonable estimate unless specific steps such as lining of canals are taken to reduce seepage. In general, it may be assumed that seepage losses return to the stream and become available for use at downstream points. Conveyance wastes have also been estimated and measured. This waste has been found to range from 1% to 60% of the diverted flow. The amount of waste seems to be dependent to a large extent on the availability of water with the higher waste occurring where water is most plentiful. Most conveyance waste also returns to the stream from which it was diverted. An estimate of 15% of the total diverted flow would not be unreasonable for conveyance waste if no data are available for a more reliable estimate.

(3) From the above discussion it is evident that from 15% to 90% of the total diverted water may be lost or wasted in conveyance and that only 30 to 50% of the remaining water is actually available for crop growth. Therefore, it may be necessary to divert from 2 to 20 times the actual crop requirements in order to successfully irrigate some areas. Tables 4 to 6 give data for estimating crop requirements for various types of common crops and summarize in tabular form the loss and waste data discussed above.

TABLE 4

ESTIMATED ANNUAL WATER REQUIREMENTS
FOR VARIOUS CROPS AT VARIOUS
IRRIGATION EFFICIENCY RANGES

	Low efficiency 30% - 35% (ac-ft/acre)	Avg Efficiency 35% - 45% (ac-ft/acre)	High Efficiency 45% - 50% (ac-ft/acre)
Pasture, alfalfa and other forage crops	6	4	2
Potatoes, sugar beets, cotton	4	2.5	1.5
Cereals (excluding rice)	3	2	1
Rice	10	8	5
Deciduous fruits	4	3	2
Small fruits, grapes	3	2	1.5
Citrus fruits	4	3	2
Vegetables	4	2.5	1

Notes:

(1) Total water requirement; precipitation immediately prior to and during growing season should be deducted to obtain irrigation requirements.

(2) Conveyance losses and wastes are not included.

TABLE 5

TYPICAL MONTHLY VARIATIONS
IN IRRIGATION REQUIREMENTS

	Small Variation	Average Variation (Percent of Annual Total)	Large Variation
January	5	0	0
February	6	0	0
March	10	2	0
April	10	13	0
May	10	20	1
June	11	19	11
July	11	19	23
August	10	13	30
September	9	10	27
October	7	3	8
November	6	1	0
December	5	0	0
Total	100	100	100

Note: Variations in time of growing season could require shifting forward or backward the tabulated monthly schedules.

TABLE 6

LOSSES AND WASTES EXPRESSED
AS PERCENTAGE OF TOTAL DIVERTED FLOW

	Low	Average	High
Conveyance loss	15	30	50
Conveyance waste	5	15	30

c. Return flow. That portion of the water diverted for irrigation purposes which returns to the stream is called return flow. Generally most of the conveyance losses and waste returns to the stream as well as a portion of the water actually applied to the irrigated lands. If the time of occurrence of return flow is of importance, as it often is when the water is used at a downstream point, studies may be required to determine the time distribution of return flows. However, the return flow (which is usually expressed as a percentage of diverted flow) is often assumed to return either during the month in which it was diverted or during the following month. A more complex pattern for return flows might be simulated by assuming various percentage of return flow in each of several successive months. For example, a general schedule for return flows might be: 60% of total return flow re-enters the stream during the month in which it was diverted, 30% returns the following month, and 10% the third month. Estimates of total return flow are as follows:

(1) Low return flow: 10% of total diverted flow plus conveyance losses and waste.

(2) Average return flow: 20% of total diverted flow plus conveyance losses and waste.

(3) High return flow: 30% of total diverted flow plus conveyance losses and waste.

d. Demand Requirements for Other Purposes. It is not feasible to present generalized demand requirements for hydroelectric power, water quality control, and low flow regulation because the demand is a function of a target output which either cannot be stated quantitatively or is prescribed by another agency. For instance, hydroelectric power demand is determined by the portion of the area load the project is expected to meet as well as the characteristics of the area load. This information is usually furnished by the Federal Power Commission in the form of a minimum year capacity and/or energy requirement. The energy requirement is usually given as an annual plant factor which may be as low as 5 or 10% for peaking plants or as high as 100% for base load plants. For detailed studies of peaking plants, it may be necessary to obtain from the FPC monthly percentages of annual total energy requirements similar to those shown for water supply and irrigation in Tables 2 and 5.

APPENDIX 4
PHYSICAL AND HYDROLOGIC CONSTRAINTS

a. Physical Constraints. Physical constraints which should be considered in storage-yield studies include the following items: (1) maximum storage available, (2) outlet capacities, (3) channel capacities. If flood control is to be included as a project purpose, the maximum storage feasible at a given site will be affected by the flood control analyses. As a rule, the net storage available for conservation uses will be reduced if flood control is included as a project purpose. Outlet capacities and channel capacities are important insofar as they affect the conservation operation and, although their effect is usually negligible, they should be given at least enough consideration to determine their importance.

b. Priorities. In order to determine optimum yield in a multiple-purpose project some type of priority system for the various purposes must be established. This is necessary when the competitive aspects of water use require a firm basis for an operating decision. Flood control usually has highest priority in a multiple-purpose project during actual operation, and hence, during periods of flood control operations, conservation requirements might be reduced in order to provide the best flood-control operation. Although this manual is not concerned directly with flood-control operation or criteria, it is necessary to evaluate flood control requirements to insure that operating conditions and reservoir levels for conservation purposes do not interfere with flood control operation. Priorities among the various conservation purposes vary with locale, with water rights, and with the need for various types of water utilization. Perhaps most generally the following priorities exist, although with many marked exceptions: (1) municipal and industrial water supply and navigation, (2) power and irrigation, and (3) water quality management and low-flow regulation. In multipurpose projects every effort should be made to develop operation criteria which maximize the complementary uses for the various conservation purposes. Unless allocation of space to specific purposes is directed, avoidance of specific allocations of space in favor of operation rules based on total remaining storage will ordinarily maximize overall accomplishments.

c. Storage Limitations.

(1) One of the reasons for making sequential routing studies is the need to determine the effect of storage limitations on yield rates. Simplified yield methods cannot account for operational restrictions imposed by storage limitations in a multiple-purpose project. There are three primary storage zones, any or all of which may exist in a given reservoir project. The three zones may generally be described as follows: first, flood control space which is usually the uppermost storage space in the reservoir; second, conservation storage which is immediately below the flood control storage; and third, reserve or dead storage which is the lowest storage space in the reservoir. The boundaries between the storage zones and operational boundaries within the zones may be fixed throughout the year or they may vary from season to season as shown on Plate 1. The varying boundaries usually offer a more flexible operation plan which may result in higher yields for all purposes, but an additional element of chance is often introduced when the boundaries are allowed to vary. The purpose of the detailed sequential routing studies is to produce an operating scheme and boundary arrangement which minimizes the chance of failure to satisfy any project purpose while optimizing the yield for each purpose. Each of the three storage zones and the effect of varying their boundaries are discussed in the following paragraphs.

(2) Flood Control Storage.

(a) The inclusion of flood-control storage in a multiple-purpose project may adversely affect conservation purposes in two ways. First, storage space which might otherwise have been utilized for conservation purposes is reserved for flood-control usage, and second, flood control operation criteria may override conservation criteria with a resultant reduction or loss of conservation benefits. However, detailed planning and analysis of criteria for flood control and conservation operations can minimize the adverse effects.

(b) Where competition between flood control and conservation requirements exists and when flood control and conservation requirements do not coincide timewise, the use of a seasonally varying boundary between flood control storage and conservation storage may be used to minimize the competition. The general procedure followed is to hold the top of conservation pool low when conservation demands are not critical in order to reserve more storage space for flood control regulation. Then, as the likelihood of flood occurrence decreases, the top of conservation pool is raised to increase the storage available for conservation purposes.

Operation criteria are then tested by detailed sequential routing for the period of flow record. Several different variations may be tried before the best variation is found.

(c) In conservation studies, flood control operation is often simplified because the routing interval for conservation studies is frequently too long to adequately define the flood control operation. When this is the case, flood control constraints are observed insofar as possible. For example, channel capacities below the reservoir are considered for flood control release purposes, and storage above the top of flood control pool is not permitted.

(3) Conservation Storage. In many multipurpose projects, the conservation storage may be used to regulate minor floods as well as supply water for conservation purposes. For this reason, a seasonally varying boundary between flood control storage and conservation storage is often advantageous to both flood control and conservation. In addition to seasonal variations in its upper boundary, the lower conservation storage boundary may also vary seasonally. If several conservation purposes of different priorities exist, there may be need for a buffer zone in the conservation storage. The seasonal variation in the boundary between conservation storage and buffer zone would be determined by the relationship between seasonal demands for the various purposes. Buffer storage may be required for one of two reasons. First, it may be used in the multipurpose projects to continue releases for a high-priority purpose when normal conservation storage has been exhausted by supplying water for both high and low priority purposes; and, second, it may be used in a single-purpose project to continue releases at a reduced rate after normal conservation storage has been exhausted by supplying water at a higher rate. In either case, the boundary between the normal conservation storage and buffer storage is used to cause a change in operation criteria. The proper location of this boundary and its seasonal variation are important factors in a detailed sequential routing because of the change they produce in operation criteria.

(4) Reserve or Dead Storage. Reserve or dead storage is the storage which is maintained in the reservoir for any one of a number of purposes. Maintenance of a recreation pool, maintenance of head for power, maintenance of reserve for sedimentation and sustenance of fish and wildlife are examples of reasons for providing reserve or dead storage. As a rule, the reservoir may not be drawn below the top of the reserve or dead storage. However, the top of the reserve may be allowed to vary seasonally in some instances. For example, if reserve storage is provided only to maintain a recreation pool, it might be permissible to withdraw water from

the reserve storage for other conservation purposes during the season when there is little or no use of the reservoir for recreation. Should such a condition exist, it would be beneficial to examine by means of detailed sequential routing the possible increase in yield for other purposes.

APPENDIX 5
COMPILATION OF BASIC DATA

a. Selection of time interval.

(1) The selection of an appropriate time interval pertains primarily to the sequential type analysis; however, similar reasoning must be applied to selection of flow periods for analysis by non-sequential methods. Time intervals of one month or longer are usually adequate for non-sequential and preliminary sequential analyses. For more detailed studies, shorter routing intervals (generally ranging from a minimum interval of one week to a maximum of one month) will ordinarily be required. Only in exceptional cases will routing intervals of less than one week be practical for entire periods of record, because of the large amount of work involved and because time translation effects (which are usually ignored in conservation routing studies) become important with intervals of less than one week. Where shorter intervals are necessary, such as during flood periods or for daily power fluctuations, these can be used for selected short periods.

(2) In sequential routing studies, the selection of a routing interval is dependent upon four major factors: (a) the demand schedule that will be utilized in determining the yield; (b) the accuracy required by the study objectives; (c) the data available for use in the study; and (d) the phase relationship between periods of high and low demands and high and low flow. If the water demand schedule is relatively uniform, it is ordinarily possible to estimate the amount of storage required for a specified yield by graphical analysis using the Rippl diagram or a non-sequential analysis. Demand schedules which show marked seasonal variations usually preclude the use of graphical techniques alone in determining storage requirements. This is especially true when the demand is a function which cannot be described in terms of a specific amount of water as in the cases of hydroelectric power and quality control. In order to obtain accurate estimates of storage requirements when the demand schedule is variable, it is necessary to make sequential routing studies with routing intervals short enough to delineate important variations in the demand schedule. Graphical techniques may be utilized in obtaining a first estimate of storage requirements for use in the detailed sequential routing.

(3) Plate 1 indicates the types of errors which might be introduced in storage determination by graphical techniques when an equivalent uniform demand schedule is assumed in lieu of a known

variable demand schedule. The variable demand schedule shown on Plate 1 is relatively simple and thus does not accentuate the errors brought about by improper selection of routing interval. The uniform rate shown is equivalent to selection of a one-year routing interval, and the difference in storage requirements shown is the error that would result from selection of a one-year routing interval rather than a shorter interval reflecting the demand schedule variation.

(4) As a general rule, increased accuracy requirements necessitate shorter routing intervals. This is due to many factors such as better definition of relationships between inflow and releases, better estimates of average reservoir levels for evaporation and power, etc. Longer routing intervals tend to reduce the characteristic variations in flows, thus producing a "dampened" storage requirement. Ordinarily a monthly or seasonal routing interval is adequate for basic studies. However, when fluctuations in flows or demands may be critical factors in determining storage requirements, it is usually necessary to refine the computations as appropriate for selected critical protions of the studies or to utilize shorter routing intervals.

(5) In general, the routing interval should not be shorter than the shortest period for which flow and demand data are available. Attempts to "manufacture" flow or demand data are usually time-consuming and may create errors or give a false impression of accuracy unless reliable information is available for subdivision of basic data.

(6) The selection of the flow interval for analysis by non-sequential methods is usually not as critical as the selection for a sequential analysis. Since the non-sequential analysis is restricted to uniform demands, it does not result in answers as accurate as those obtained by sequential methods, and therefore the gain in accuracy when selecting short intervals is not so great. Flow intervals of one month are usually suitable for non-sequential methods.

b. Inflow data.

(1) It is becoming increasingly rare that flow data as recorded are satisfactory for direct use in project studies. Usually flow information is required at locations other than gaging stations and for conditions of upstream development other than those under which flows occurred historically. Where estimates of flows are necessary, these are usually made by correlation with stations having records for the desired time or by adjustment of such records on the basis of tributary area and other hydrologic factors. In deriving and applying the required relationships, it is desirable to use "natural" flows in order that correlation procedures will apply efficiently. Where synthetic inflows are to be obtained, as with a stochastic generation process, it is even more desirable that natural flows be used,

because general frequency functions characteristic of natural flows are employed in this process.

(2) It is not always feasible to convert flows to natural conditions. Required data might not be available or the flow modification might be so complex as to require an unreasonable amount of computation. When feasible, conversion is made by adding historical storage changes (plus net evaporation) and upstream diversions (less return flows) to historical flows at the gaging stations for each interval in turn. Under some conditions, it is necessary to account for differences in channel and overbank percolation losses, distributary flow divisions, travel times and other factors. When it is not feasible to convert flows completely to natural conditions, they should be adjusted, if only approximately, to a uniform condition, such as present conditions. In such cases, every reasonable effort should be made to remove special influences such as one major reservoir that would cause unnatural variations of flow.

(3) After recorded flows are converted to a uniform condition, flows for missing periods of record at each pertinent location should be estimated by correlation with recorded flows at other locations in the region. Usually only one other location is used and linear correlation of flow logarithms is used. It is much more satisfactory, however, to use all other locations in the region that can contribute independent information on the missing data. Although this would require a large amount of computation, a computer program to accomplish this for monthly streamflows is under development in the Hydrologic Engineering Center. Flow estimates for locations where no record exists can be estimated satisfactorily on a cfs-per-square-mile basis in some cases, particularly where a gage exists on the same stream. In most cases, however, it is necessary to correlate mean flow logarithms (and sometimes standard deviation of flow logarithms) with logarithm of drainage area size, logarithm of normal seasonal precipitation, and other basin characteristics. Correlation procedures and suggested basin characteristics are contained in reference 3.

(4) After project flows for a specified condition of upstream development are obtained for all pertinent locations and periods, they must be converted to pre-project or non-project conditions. Non-project conditions are those that will prevail during the lifetime of the proposed project if the project is not constructed. This conversion is made by subtracting projected upstream diversions and storage changes, accounting for evaporation, return flows and differences in channel percolation, timing, etc.,

where appreciable. Where non-project conditions will vary during the project lifetime, it is ordinarily necessary to convert to two or more sets of conditions, such as those at the start and end of the proposed project life. Separate operation studies would then be made for each condition. This conversion to future conditions can be made simultaneously with project operation studies, but a separate evaluation of non-project flows is usually required for economic evaluation of the project.

c. Reservoir losses. The non-project inflow into a proposed reservoir is determined by making necessary adjustments to recorded flow data as discussed above. This inflow represents the flow at the project site without the reservoir and includes runoff from the entire effective drainage area above the dam, including the reservoir area. Under non-project conditions, runoff from the area to be inundated by the reservoir is ordinarily only a fraction of the total precipitation which falls on that area. However, because percolation losses are virtually eliminated at most reservoirs, practically all of the precipitation falling on the reservoir area under project conditions will appear as runoff. The inflow will therefore be greater under project conditions than under non-project conditions, if inflow is defined as total contribution to the reservoir before evaporation from the reservoir water surface. In order to determine the amount of water available for use at the reservoir, evaporation must be subtracted from project inflow. In operation studies, non-project inflow is ordinarily converted to available water in one operation, without computing project inflow as defined above. This is done in one of two ways - as a constant annual loss each year with seasonal variation or as a different loss each period expressed as a function of observed precipitation and evaporation. These two methods are as follows:

(1) The constant annual loss procedure consists of estimating the evapo-transpiration and infiltration losses over the reservoir area for conditions without the project, and the evaporation and percolation losses over the reservoir area with the project. Non-project losses are usually estimated as the difference between average annual precipitation and average annual runoff at the location, distributed seasonally in accordance with precipitation and temperature variations. These are expressed in inches of depth. Under project conditions, percolation losses are usually ignored, and losses are considered to consist of only direct evaporation from the lake area expressed in inches for each period. The difference between these losses is the net loss due to the project. Plate 2 shows graphically the differences between non-project and project losses.

(2) The second method used to account for the change in losses due to a reservoir project is based on historical records of long-term average monthly precipitation and evaporation data. This is accomplished by estimating the average runoff coefficient for the reservoir area under pre-project conditions and subtracting this from the runoff coefficient (usually 1.0) on the reservoir area under project conditions. The difference is the net gain as a ratio of precipitation falling on the reservoir (often estimated to be .7 for semi-arid regions). This increase in runoff is subtracted from gross reservoir evaporation (often estimated as .7 of pan evaporation) to obtain a net loss. Plate 3 is an example of this method.

d. Other Losses.

(1) In final project studies it is often necessary to consider other types of project losses which may be of minor importance in preliminary studies. In many cases these losses cannot be estimated until a project design has been adopted. The importance of these losses is dependent upon their relative magnitude. That is, losses of 50 cfs might be considered unimportant on a stream which has a minimum average annual flow of 15,000 cfs; but on a stream with a minimum average annual flow of 250 cfs, losses of 50 cfs would be of considerable importance. It should be noted that the term "losses" may not actually denote a physical loss of the water. Usually water which is unavailable for a specific project purpose is called a "loss" for that purpose although it is not actually lost if it can be used at some other point or for some other purpose. For example, water which leaves the reservoir through a pipeline for purposes of municipal water supply or fish hatchery requirements might be called a loss to power. Likewise, leakage through turbines, dam, conduits, and spillway gates are considered losses to power but they are ordinarily not losses insofar as flow requirements at a downstream station are concerned. Furthermore, such losses as leakage through the dam, turbines, conduits, and gates become available for use below the dam and should be added to inflows to points downstream from the project. Various types of losses are discussed in the following paragraphs and the purposes to which they pertain are also listed.

(2) Losses to purposes which are dependent upon water available at the dam or in the reservoir.

(a) All types of leakage at a dam or in a reservoir area are considered as losses to purposes which are dependent upon availability of water at the dam or in the reservoir itself; i.e., power generation, pipelines from the reservoir, and any purpose which utilizes pump intakes which are located at or above the dam. Leakage is ordinarily not a loss to purposes which are dependent upon water released from the reservoir; i.e., low flow augmentation, water quality at a downstream control station, and other purposes which require withdrawal of water from the stream below the dam. Some of the commonly encountered types of leakage are described in the following paragraphs.

(b) Leakage through, around, and under a dam. As a rule this type of leakage is difficult to estimate before a project is actually constructed. In some cases the measured leakage at a similar type dam or in a similar geologic area may be used as a basis for estimating losses at a proposed project. The amount of leakage is a function of the type and size of dam, the geologic conditions, and the pressure caused by water in the reservoir.

(c) Leakage from conduits and spillway gates. Leakage from conduits and spillway gates is a function of gate perimeter, type of seal, and head on the gate. The amount of leakage may be measured at existing projects with various types of seals and a leakage rate per foot of perimeter at a given head can be computed. This rate may then be used to compute estimated leakage for a proposed project by using the proposed size and number of gates and the proposed head on the gates.

(d) Leakage through turbines when closed. If a proposed project is to include power and if the area demand is such that the turbines will be idle some of the time, it is advisable to estimate the leakage through the turbines when closed. This leakage is a function of the type of penstock gate, type of turbine wicket gate, number of turbines, and head on the turbine. The actual leakage through a turbine may be measured at the time of acceptance and during annual maintenance inspections, and the measurements of comparable existing projects may be used to estimate leakage for a proposed project. An estimate of the percent of time that a unit will be closed may be obtained from actual operation records for existing units in the same demand area. The measured leakage rate is then reduced by multiplying by the proportion of time the unit will be closed. For example, suppose that leakage through a turbine has been measured at 10 cfs and the operation records indicate that the unit is closed 60% of the time. The average leakage rate would be estimated at 10X0.6 or 6 cfs.

(e) Leakage through navigation locks. The inclusion of a navigation lock at a dam requires consideration of lockage and leakages through the lock. The leakage is dependent upon the lift or head, the type and size of lock, and the type of gates and seals. As is the case for other types of leakage it can usually be estimated from observed leakage at similar type structures.

(f) Station use, house units, cooling and condensing. Use of water for purposes related to operation of a project is often treated as a loss. Station use for sanitary and drinking purposes, cooling water for generators, and water for condensing operations have been estimated to be about 2 cfs per turbine at some stations in the southwest. Examination of operation records for comparable projects in a given study area may also be useful in estimating these losses. If house units are included in a project (to supply the project's power needs), data should be obtained from the designer in order to estimate water used by the house unit or units.

(3) Losses to purposes which are dependent upon water released from the reservoir. Only those losses which leave the reservoir area and do not return above the downstream use points are losses to purposes dependent upon water released from the reservoir. Examples of this type of loss would be deep percolation and leakage from the reservoir area which re-enters the stream below a downstream use point or control station.

(4) Competitive use of water. In initially estimating yield rates for various project purposes at a multiple-purpose project, the engineer often treats competitive uses of water as losses in order to improve his estimate. For example, assume a stream with a minimum average annual usable flow of 160 cfs. If a project proposed for that stream will furnish water supply by a pipeline from the reservoir at an average rate of 15 cfs, fish hatchery releases of 20 cfs through a pipeline, and also will produce hydroelectric power, the minimum average flow available for for power generation is 160-(15+20)=125 cfs. Care should be exercised in accounting for all competitive uses when making preliminary yield estimates.

e. Shortage tolerances. The shortage tolerances for various project purposes can greatly influence the amount of storage required to produce a "firm" yield. These tolerances differ considerably for different project purposes throughout the nation. The best picture of the shortage tolerances can be seen by reviewing design criteria for individual project purposes.

(1) Hydroelectric Power. Hydroelectric power facilities are usually designed for the most adverse observed streamflow conditions. However, the most critical period of streamflow records, as shown in reference 4, can be far different from conditions that might occur in the future. For a system analysis of hydroelectric power projects, shortages for individual reservoir projects can be tolerated as long as the overall system plant factor is not shorted. To the extent that interties permit, hydroelectric power requirements can be generated from the reservoirs that are not experiencing a severe drawdown, thereby taking advantage of the less-severe system drought.

(2) Municipal and Industrial Water Supply. Municipal and industrial shortages fall into the same general category as hydroelectric power in that shortages are intolerable for purposes such as drinking water. However, some reduction in the quantity of water required for M&I purposes can be tolerated without serious economic effects by reducing some of the less important uses of water such as lawn watering, car washing, etc. These reductions are in the order of 10%. Most designs for M&I storage are based on supplying the firm yield during the most critical period of flow record, with some reserve storage for use in the event of unprecedented droughts. Another approach to shortage tolerances for M&I is to design on a shortage probability basis, such as a 1% or a 2% probability of shortage per year.

(3) Irrigation. Shortages for irrigation are acceptable under various conditions. Some designers would accept one 50% annual shortage during the economic life of a proposed project, while others may accept 5 or 10 shortages of as much as 10% or 20% without adversely affecting the economics of the project.

(4) Water Quality. Water quality shortage tolerances are usually expressed in terms of shortage probability. A 10% or a 20% probability of shortage during any year is often considered reasonable in determining the storage requirements for water quality purposes, according to the Federal Water Pollution Control Administration.

(5) Shortage Index. A general approach to shortage definition is to use some sort of a shortage index like that proposed in reference 15. The shortage index, as defined in that publication, is equal to the sum of the squares of the annual shortages over a 100-year period, when each annual shortage is expressed as a ratio to the annual requirement. The significance of the shortage index can be illustrated as follows:

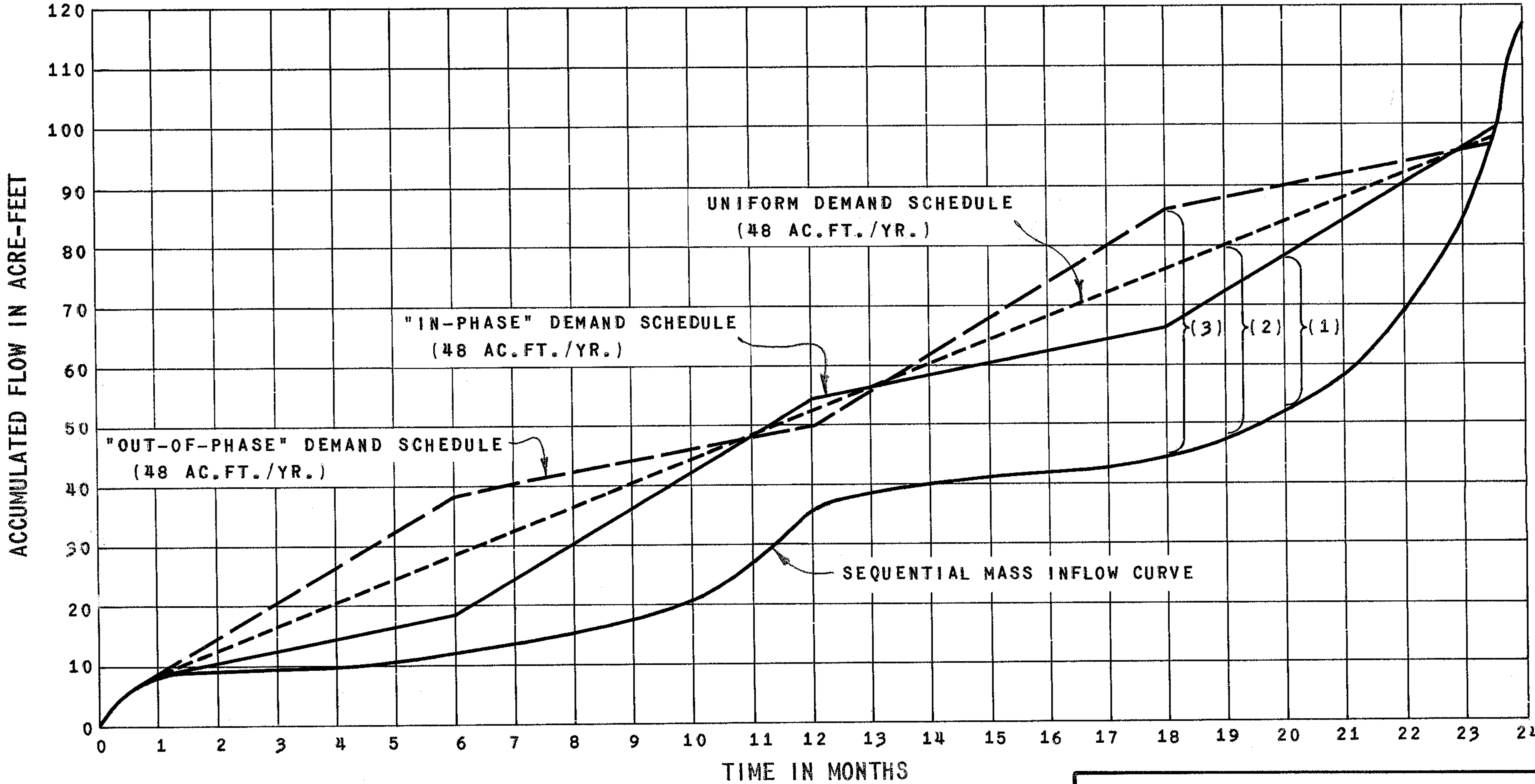
TABLE 1

ILLUSTRATION OF SHORTAGE INDEX

Shortage Index	No. of Annual Shortages Per 100 Years	Annual Shortage In Percent
1.00	100	10
1.00	25	20
1.00	4	50
.25	25	10
.25	1	50

This shortage index reflects the observation that economic and social effects of shortages are about proportional to the square of the degree of shortage, and therefore has considerable merit over shortage frequency alone as measure of severity, since shortage frequency concerns only frequency and not magnitude and duration. The shortage index can be multiplied by a constant to obtain a fair estimate of associated damages.

(6) Future Needs. It is apparent that there is considerable need for criteria delineating shortage acceptability for various services under various conditions. These could be based on social and economic costs of shortages in each individual project study, or certain standards could be set for the various services and conditions. Such criteria should account for degree of shortage as well as expected frequency of shortage.



(1) STORAGE REQUIRED TO YIELD 48 AC.FT./YR. WHEN DEMAND SCHEDULE IS "IN-PHASE" WITH FLOW PATTERN ≈ 26.5 ACRE FEET

(2) STORAGE REQUIRED TO YIELD 48 AC.FT./YR. WHEN DEMAND SCHEDULE IS UNIFORM ≈ 33.0 ACRE FEET

(3) STORAGE REQUIRED TO YIELD 48 AC.FT./YR. WHEN DEMAND SCHEDULE IS "OUT-OF-PHASE" WITH FLOW PATTERN ≈ 41.5 ACRE FEET

EFFECT OF DEMAND SEQUENCE
ON STORAGE REQUIREMENTS

HYDROLOGIC ENGINEERING CENTER

CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA

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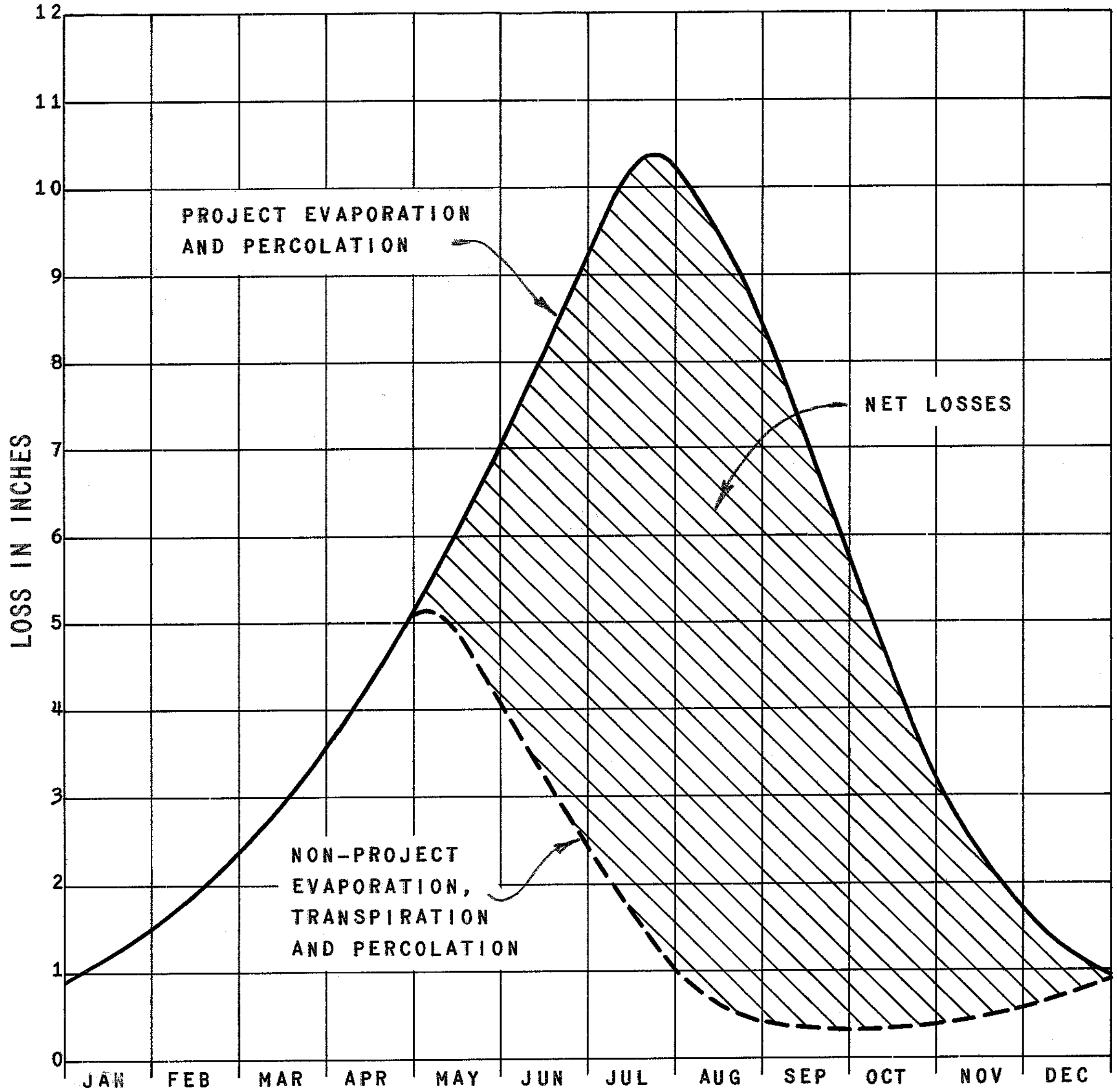

PROJECT AND NON-PROJECT
RESERVOIR LOSSES

HYDROLOGIC ENGINEERING CENTER

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SAMPLE COMPUTATION OF AVERAGE NET RESERVOIR LOSS

	AVERAGE (1) PAN EVAPORATION (inches)	AVERAGE (2) GROSS RESERVOIR EVAPORATION (inches)	AVERAGE (1) PRECIPITATION (inches)	AVERAGE (3) POST-PROJECT INCREASE IN RUNOFF (inches)	AVERAGE (4) NET RESERVOIR LOSS (inches)
JANUARY	1.68	1.18	2.10	1.26	- .08
FEBRUARY	2.50	1.75	2.41	1.45	+ .30
MARCH	3.28	2.30	1.96	1.18	+ 1.12
APRIL	5.90	4.13	3.28	1.97	+ 2.16
MAY	5.35	3.75	4.81	2.89	+ 0.86
JUNE	7.33	5.13	1.59	0.95	+ 4.18
JULY	9.18	6.43	1.28	0.77	+ 5.66
AUGUST	8.81	6.17	1.39	0.83	+ 5.34
SEPTEMBER	6.81	4.77	1.16	0.70	+ 4.07
OCTOBER	3.40	2.38	1.15	0.69	+ 1.69
NOVEMBER	1.76	1.23	.57	0.34	+ .89
DECEMBER	1.29	.90	1.82	1.09	- .19
TOTAL	57.29	40.12	23.52	14.12	26.00

NOTES:

(1) Long term monthly averages from climatological records.

(2) In this example it has been assumed that the reservoir evaporation is 70% of the pan evaporation in all months. However, the percentage may vary from month to month.

(3) In this example it has been assumed that under pre-project conditions 40% of the precipitation appeared as runoff in each month and therefore the post-project increase in runoff is 60% of the precipitation. In some cases it might be necessary to have the percentage of increase in runoff vary from month to month in order to accurately represent the historical conditions.

(4) Average net reservoir loss is the average gross reservoir evaporation minus the average post-project increase in runoff. Positive values of average net reservoir loss indicate that post-project losses exceed gains and negative values indicate that post-project gains exceed losses.

APPENDIX 6
COMPUTATION AIDS

a. Two of the most useful and time-saving computation aids are elevation-capacity and area-capacity tables or curves with capacities in the same units as inflow. For example, if a weekly routing study is to be performed using inflows in cfs-weeks (week-second-feet) it is advantageous to compute a capacity table in cfs-weeks before beginning the study, and then the entire routing may be made in the same units, eliminating the time-consuming process of unit conversion for each routing period. Elevation-area-capacity tables for any units can be readily computed at .1 foot intervals of elevation by the use of the Hydrologic Engineering Center's computer program 23-J2-L233. Sample elevation-area-capacity tables in flow units as computed by program 23-J2-L233 are shown as Plate 1.

b. Another example of a useful computation aid is the KW/CFS nomograph for use in power routing studies. This nomograph is prepared prior to beginning a power routing study and it incorporates all of the physical data required to determine a power release for a given amount of power generation. Plate 2 shows the computations necessary to develop a KW/CFS curve and the method for constructing the nomograph. Note that the nomograph has been prepared for use in a weekly power routing where flows in cfs-weeks are to be used, and thus storage in cfs-weeks is utilized as the storage units for the nomograph.

c. It is necessary to exercise ingenuity in developing computation aids which will significantly decrease the time required to perform a manual routing study, particularly if the proposed study is lengthy or if a series of studies is to be made and if electronic computer facilities cannot be employed.

d. Some frequently used conversion constants are given in Plate 3.

ILLUSTRATIVE RESERVOIR AREA AND CAPACITY TABLE

ELEV FEET	CAP AREA .0	CAP AREA .1	CAP AREA .2	CAP AREA .3	CAP AREA .4	CAP AREA .5	CAP AREA .6	CAP AREA .7	CAP AREA .8	CAP AREA .9
620.0	29354 30510	29421 30550	29470 30590	29520 30630	29570 30570	29620 30710	29669 30750	29719 30790	29769 30830	29818 30870
621.0	29888 30910	29918 30950	29968 30990	30017 31030	30084 31070	30133 31110	30183 31150	30233 31190	30283 31230	30332 31270
622.0	30382 31310	30432 31350	30498 31380	30548 31420	30597 31460	30647 31500	30697 31530	30747 31570	30796 31610	30863 31650
623.0	30912 31680	30962 31720	31012 31760	31062 31800	31111 31830	31178 31870	31227 31910	31277 31950	31327 31980	31376 32020
624.0	31443 32060	31493 32100	31542 32140	31592 32180	31658 32220	31708 32260	31758 32300	31807 32340	31857 32370	31923 32410
625.0	31973 32450	32023 32490	32073 32530	32139 32570	32189 32510	32238 32650	32288 32690	32354 32730	32404 32770	32454 32810
626.0	32520 32850	32570 32890	32620 32930	32669 32960	32736 33000	32785 33040	32835 33080	32901 33120	32951 33150	33001 33190
627.0	33067 33230	33117 33270	33167 33300	33233 33340	33283 33380	33332 33420	33399 33460	33448 33500	33498 33530	33564 33570
628.0	33614 33610	33604 33650	33730 33680	33780 33720	33846 33760	33896 33790	33946 33830	34012 33870	34062 33910	34111 33940
629.0	34178 33980	34227 34020	34294 34050	34343 34090	34393 34130	34459 34160	34509 34200	34575 34240	34625 34280	34691 34310

SAMPLE KW/CFS NOMOGRAPH FOR POWER ROUTINGS

KILOWATTS/CFS COMPUTATION - RESERVOIR AAA

Pool Elevation (ft, m.s.l.)	Storage(1) (WSF÷1000)	Net head(2) (ft)	Efficiency(3) (%)	KW/CFS(4)
1132	145.2	203.5	83.2	14.34
1128	136.0	199.5	84.0	14.19
1124	127.3	195.5	84.6	14.01
1120	119.0	191.5	85.1	13.80
1116	111.0	187.5	85.5	13.58
1112	103.5	183.5	85.9	13.35
1108	96.3	179.5	86.1	13.09
1104	89.5	175.5	86.3	12.83
1100	83.0	171.5	86.1	12.51
1096	76.9	167.5	85.9	12.19

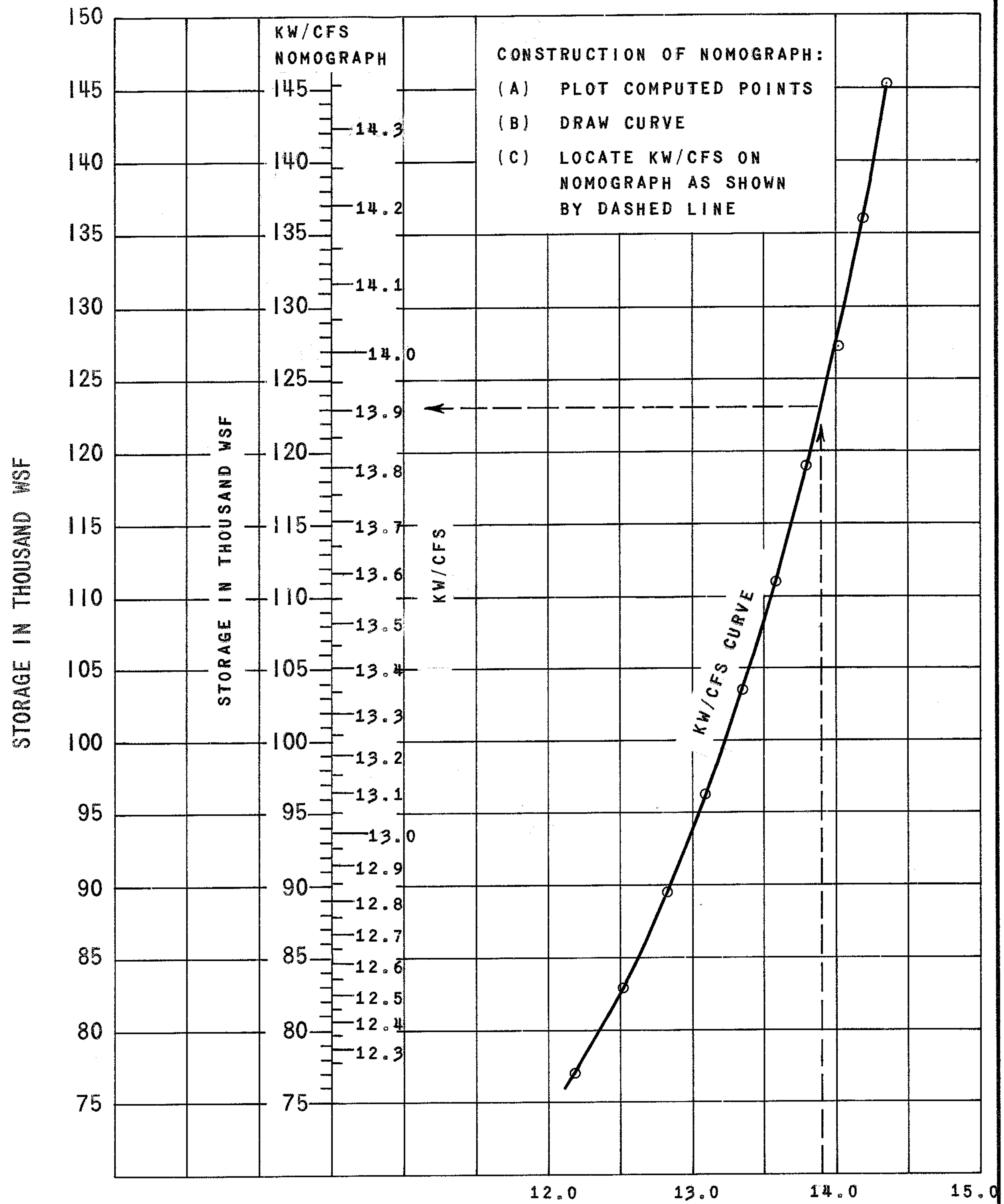
Based on constant avg. tailwater @ elev 927.8 ft, m.s.l.
with assumed constant penstock losses of 0.7 ft

(1) The use of storage in week-second-feet for this example is based upon the selection of a week as the routing interval and week-second-feet as the flow units.

(2) Net head = Pool elev. - penstock losses - avg. tailwater (Both penstock loss and avg. tailwater may be varied with pool elevation if relationship is known)

(3) Overall station efficiency (may be assumed constant at all pool elevations)

(4) KW/CFS = Head X Eff X .08474



SAMPLE KW/CFS NOMOGRAPH
FOR POWER ROUTINGS

HYDROLOGIC ENGINEERING CENTER

CORPS OF ENGINEERS, SACRAMENTO, CALIFORNIA

Prepared: Date:

CONVERSION CONSTANTS

24 hour-cfs	= 1.9835	acre-feet
28 day-cfs	= 55.538	" "
30 day-cfs	= 59.505	" "
31 day-cfs	= 61.489	" "
30.475 day-cfs	= 60.373	" "
1 week-cfs	= 13.8843	" "

1 inch square mile = 53.3333 acre-feet

1 cfs = 724 acre-feet/year

1.55 cfs = 1 mgd

1 cfs = 448.83 U.S. gallons per min.

.167 inches/week	= cfs/1000 acres
.667 inches/28 day	= cfs/1000 acres
.714 inches/30 day	= cfs/1000 acres
.724 inches/30.47 days	= cfs/1000 acres
.737 inches/31 days	= cfs/1000 acres
8.688 inches/year	= cfs/1000 acres

APPENDIX 7
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